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Rumford Professor and Lecturer on the Application of Science to the Useful Arts
1834–1845

THE MYSTERY OF MATTER AND ENERGY

RECENT PROGRESS AS TO THE STRUCTURE OF MATTER

BY

ALBERT C. CREHORE, PH.D.

ILLUSTRATED

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TO

W. D. S.

Preface

CASUAL perusal of the brief sketch herein cannot fail to reveal the motive in writing it. It is the hope of creating more enthusiasm in the pursuit of the goal. If more people fully realized what the goal is, it is believed that more serious efforts would be directed to its attainment. So our efforts are directed almost entirely toward making a statement of the nature of the ends to be attained, in the hope that the mere statement will have the effect, in some way and among a certain class of thinkers, of arousing more enthusiasm. Enough has been said in this account to make it evident that there is much labor connected with the prosecution of the work, and that the laborer should have the sympathetic support and encouragement of all those in a position to give it.

History shows that, almost without exception, practical use is eventually made of all of the fundamental truths of nature that man has acquired, and that the discovery of them is the

essential thing; essential as well for moral as for material progress.

There is no attempt to cover the whole range of physical knowledge with any approach to completeness, and no apology is offered for giving some account of the part that the author has taken in the work. He is naturally in a better position to speak of this than of the work of others. It is believed that a readable account of these investigations will be welcomed by some for the reason that the results are stated without the use of mathematical language which the originals necessarily contain.

No statements have been introduced that the author does not believe will eventually prove to have been well founded. The fact that they are not all established as yet has not deterred the author from introducing them. With this confession he has no fear that the reader, who is not especially familar with the present state of Physical Science, will be misled by anything that is said.

ALBERT C. CREHORE

YONKERS, N.Y.
April, 1917.

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REFERENCES

No list of references to the literature bearing upon the subjects above treated has been prepared because these may be found in other works. Reference may be had to Comstock and Troland's "The Nature of Matter and Electricity" which is very complete with references.

For the mathematical theory of the applications of electro-magnetic theory to matter in its steady state, see the author's paper in the Physical Review, June, 1917.

The Mystery of Matter and Energy

I

NE of the purposes of the following lines will be fully accomplished if we succeed in presenting to those who have given little thought to this subject some conception of what is implied by the words "the problem of the structure of matter." Among scientists this problem has gradually increased in importance to such an extent that it may now be said to be the problem of problems. Some years ago the desirability of its solution was recognized, but its actual accomplishment seemed so improbable that it did not arouse the enthusiasm which is necessary to cause any problem to assume the first place. As eminent an authority as Tait said that "the discovery of the ultimate nature of matter is

probably beyond the range of human intelligence."

The rapid developments of the last two decades have opened upon our view, as it were, a new universe entirely unknown to the author of this quotation, and unsuspected by anybody. With this new acquisition of knowledge the problem of problems has received a fresh impetus. The improbability of its solution in the eyes of a former generation has, it may be said, been changed into a probability in the eyes of the present generation. Keeping in view the prospect of a successful outcome, the necessary enthusiasm has been created to place this problem in the first rank, making it second to none.

It will become clear that it can be second to none only after a comprehensive statement of the problem is made, for, it will then appear that other problems are necessarily subordinate and secondary, being included in the one when interpreted in its broadest sense. But, to make a statement of it requires that something be known of the nature of its solution, for, it has been said that if a complete statement of a problem can be made, it is half solved. We will confine ourselves in the following remarks to

an attempt at a partial statement of this problem, which now holds the field.

An army of scientific workers has been engaged now for some years in the making of observations and exact measurements of the phenomena of nature all about us according to the modern scientific spirit. These are to be carefully distinguished from observations not made in accordance with this spirit. The modern scientific method may be said to date from about the time of Galileo, when men began to lay aside all prejudice and preconceived ideas as to how nature is really constituted, and to make an exact catalogue of things and events as they actually saw them. The distinguishing characteristic of the present-day observer is his freedom from all prejudice, his willingness to record things as he observes them. This quality has made him keen to notice all events of an unusual character, and, in recording his observations of them, has led him to discover many of the hidden truths of Nature, which would otherwise have remained in the great unknown.

But, this is not a fair conception of the modern observer. It suggests that his work might be

done almost as well by a good machine. Indeed, a part of it might, but the observer adds to his admirable automatic qualities the power of the human mind to reason from those things he observes to other more subtle or elusive things he has not observed directly, so to speak, but, which must be true if certain great principles are admitted as established. The principle of the "conservation of energy," for example, has been perhaps the source of the most fruitful deductions from phenomena directly observed to those that follow as a necessary consequence. It is his ability to see these deductions that necessarily follow, to see the relations between one set of observations and another by a kind of intuition, as it were, where complete formal proof is lacking, to eliminate a large portion of his work as unnecessary because he sees how it must be, to arrange and classify things so as to be able to reject the non-essential and pick out the kernel of the matter without hesitation, that distinguishes the successful man who accomplishes results from his less observant brethren.

Thus, there is about the same variety of men within the special group of scientists as there is

variety in the minds of men in any of the other walks of life, and they are divided as to numbers in about the same proportion. The number of men who are capable of taking from the vast storehouse of information collected by the army of observers certain of their results, and, by subjecting them to the reasoning processes of deduction and induction, are able to generalize, and thereby discover a few fundamental principles, which, if true, simplify and connect together upon one common foundation a varied variety of apparently unrelated phenomena, these are the elect, the chosen few. But, the direct observations of the army of workers must necessarily precede such work as this, for it is they who furnish the material with which the building is to be erected upon its foundations. They must constitute the final court of appeal. Before the architect can conceive his plans, he must be well acquainted with the materials at his disposal. The analogy is helpful, perhaps, but no analogy should be pressed too far. Even when an architect is well acquainted with his materials, he still has much freedom in the manner and form in which they may enter his structure. Not so with the architect to whom

we have compared the chosen few. It is with him as if each brick, stone or timber were already cut and hewn to fit but a single building, and it rests with him to discover the plan of this building merely by an examination of the constituent parts.

It is true, and it stands to reason that it must ever be true, that the results accumulated by the observers are in excess of those of their results which the theorist has appropriated and digested. Neither should it be expected that the human mind can, independently by its own power, arrive at any great generalization which solves the riddle of the universe. If ever any such generalization is attained, it will, no doubt, be by the old and valuable process of "trial and error." One theory has its allotted life, serving a good purpose while it lives. It is supplanted because the observers keep finding things that cannot be included in the older restricted theory. A theory, which has once proven its usefulness and has been well established, is seldom displaced by the new discoveries, but is more apt to be included in a new theory of greater generality, the older theory appearing, perhaps, as a special case of the new, true only

when certain conditions are satisfied — which conditions always had been satisfied before.

It has been a discouraging and disheartening thing for many, who have not looked at the matter in this light, to find throughout the history of science one theory giving place to another and again to another, sometimes in quick succession. The impression is given that everything is fleeting, that all is built upon shifting sands. If I meet with any success in removing these obstacles to progress, this alone will have been worth the effort. These are the worst kind of obstructions because they strike at the very motive which actuates a man. In answering the question 'is it all worth while' in the negative, we deal the death blow to all enthusiasm, which is after all the main-spring of power.

On the contrary, these changing theories with the march of time should be regarded rather as an index of virility and a healthy state of life. For, it makes these products of the mind no exception to the general rules applying to all the rest of our experience, and leads us to expect and look for modifications in accepted theories rather than to be shocked at new discoveries that seem at first sight to upset the existing order of things.

The unavoidable result of entertaining these ideas is to free us at once from too great a reverence for authority and existing laws. They are useful only so far as they give results that are in harmony with the facts as we know them.

By what has been said, it will be apparent that there may be much confusion in interpreting the actual results of the observers. This is more especially true in observing electrical and atomic phenomena, because they make no appeal directly to our senses, and the observations are necessarily indirect, made by the aid of intermediate instruments, which are responsive to the phenomena being studied. For example, to measure an electric current, we observe the motion of the pointer of the ammeter, or we listen to the sound of a telephone receiver and adjust things until it vanishes in using the zero method, or we deposit a metal by electrolysis and weigh the deposit and measure the time required to make it. The value of the current is deduced from these observations, but, this operation has become so common, always giving consistent results, that the idea that we are actually observing the current is usually substituted for the actual observations. We do not suspect that any error results

from this in this simple case, but, when this mode of procedure is carried to excess, it is entirely possible that it might lead to error. In some of the more complex cases a whole series of such steps becomes necessary, and it is not an unknown occurrence that two, or even more, interpretations of the same observations are possible. So that the precedent of substituting the deduced result for the more direct observations has made it necessary to exercise great caution in the interpretation of results.

In trying to present a comprehensive view of the problem of the structure of matter, it is not intended to repeat here a catalogue of the many experimental observations that have been subjected to the most careful scrutiny from every point of view, the same results being obtained by entirely different methods, until they have come to be regarded as established facts, for these may be found in most of the textbooks. It is intended, rather, to mention a few of them that have the most direct bearing upon this subject as it is developed. At the beginning it may be stated that several theories of the constitution of matter have been formulated as a result of more recent discoveries, but not one of

them has been shown to be a complete solution of the problem. Neither shall we be able to suggest any complete solution, but this should not be allowed to diminish our enthusiastic pursuit of the goal. By this is meant that we either have not been able to deduce from the fundamental hypotheses proposed some phenomena admitted as established, or that we feel we have been able to show that certain established facts are diametrically opposed to the hypothesis. In either case, it may be the processes employed in deducing the phenomena from the hypotheses instead of the hypotheses that are wrong, and the true solution may eventually be found by changing only one or both of these. We will not consider that the solution is found until everything fits so far as we are able to go.

The first great step toward a solution of this problem was taken when it became certainly established that matter is not a continuous medium as it appears to the eye to be in the case of liquids and many solids. All substances are now known to be composed of discrete individual units or atoms, and of the hundreds of thousands of different kinds of matter in the world as we find it, the chemists have been able to pull them

all to pieces or analyze them, and they find the astonishing result that they are built of not more than a hundred different kinds of atoms. The immense number of the compounds is produced merely by the permutations and the combinations of these individual units, which appear to be the same everywhere. Even when different kinds of atoms enter in exactly the same proportions into a compound, the compound may still have very different properties. This is because the permutations of the atoms may be different when the combination is the same, and any difference whatever produces a characteristic property of the compound, different from all other compounds. The chemist feels that he is almost personally acquainted with each of these different kinds of atoms, and can recognize them from whatever source they may be derived. He distinguishes, too, among them certain family likenesses and differences, brothers, cousins, and similar groups. Each of them has been weighed with the greatest care and no variation whatever has been detected with certainty in the weights of any one of them. This led to the enunciation of a great principle which found its way into all the textbooks of a genera-

tion ago, that of the conservation of matter. In the words of one of these "whatever the changes which take place in matter, its mass remains constant. So far as science can determine not a single particle of matter has ever been brought into existence by any human agency; and no operation performed by man has ever diminished by a single atom the quantity of matter in the universe." If we take the word "particle" in the first clause of this to be equivalent to atom, then we may say that the more recent discoveries in connection with radioactive bodies have certainly proved that this statement is not true of the individual atoms at least. And, not being true of the individual atoms, we are reluctant to generalize once more and maintain that it is true of the total, or true at all. This does not mean that we assert the contrary to be the truth, it merely means we do not know that the above statement is true.

II

NOTHER great step in the solution of the problem was taken when Sir J. J. Thomson discovered a new body having a mass only 1/1845 part of that of the hydrogen atom. The lightest of the atoms composing the mass of the earth is that of hydrogen, and the heaviest that of uranium, which is 236.6 times heavier than the hydrogen atom; each of the atoms of the other elements weighing somewhere between these two comparatively narrow limits. This body, at first called a corpuscle by its discoverer, and now called an electron, is so very much lighter than the heretofore lightest known body, the hydrogen atom, that it could hardly be put in the same class with the atoms and called the atom of another element. The ratio of the mass of the hydrogen atom to that of the electron is 7.8 times as great as the ratio of the heaviest to the lightest atoms known.

There is, however, a unique characteristic that distinguishes this body from the atoms of

the elements. The electron is always associated with a negative charge of electricity, while the atoms of the elements in their ordinary condition in the earth appear to have no charge, or, if they have any, the negative is exactly neutralized by an equal amount of positive charge. A closer study of the atoms since the discovery of the electron has made it probable that the atoms themselves are really made up of nearly equal amounts of positive and negative electrical charges; for, it has been possible to examine the atoms under different conditions from the ordinary passive state, and it is then found that they sometimes become charged with electricity. The electrical charge on an electron has been estimated in a variety of ways and measured with accuracy in others, and the remarkable fact has been established that in all these ways the charge upon one electron is equal to that upon any other, no matter where it is found. One of the methods of proving this important fact deserves especial mention, the oil-drop method of Millikan.

The apparatus is so arranged that the individual droplets of a very fine spray of oil may be observed in the field of a very powerful micro-

scope as they float in the air. For this purpose the ultramicroscope is employed, that is to say, a transverse beam of light, that does not enter the microscope, illuminates the oil-drops, which are then seen as points of light against a dark background. Due to the very small size of the droplets, they fall very slowly under the action of their own weight, and with a constant velocity. This velocity with which they fall may be observed by means of the microscope, and in this way the size of the droplet may be found, because a definite law connecting the speed of fall with the size of the small particle has been established, and, knowing the one, the other may be found.

It is arranged also in this apparatus that the space where these droplets are being observed is between the two plates of an electrical condenser, so that the droplets may be observed falling in the presence of an electric field of known intensity. The presence of this field will make no difference in the speed of fall of the droplet unless it becomes charged with electricity, but, if it does become charged, the action of the electric field in which it exists is added to the effect of its weight, and, by adjusting the

polarity and the intensity of the field, the droplet may be made to fall faster or slower than before, or to rise instead of fall, and thus its speed may be controlled. Lastly, an arrangement is made to ionize the air where the droplets are floating, which may be done in a number of ways, but the process in any method projects free electrons into the space where the droplets are suspended. The drop under observation then captures one or more of these free electrons, and at the moment of capture its velocity suddenly changes. It may remain for a time moving with this new velocity, and then suddenly change again, having given up one of its electrons or captured a new one. By observing the same droplet for a long time, during several captures and discharges of electrons, and measuring the speed each time, it has been proven that its electrical charge increases suddenly by an exact multiple of a fixed minimum amount, the charge of one single electron. The observer can tell from the velocity by just how many electrons the charge changes each time.

In this manner not only has the fact that the charge on different electrons is the same been established, but, the absolute value of the charge

as well has been found to be 4.77×10^{-10} electrostatic units.

Having established the constancy of weight of the atoms, and the constancy of charge on the electron together with its small mass compared with the hydrogen atom, and coupling these facts with the observation that electrons appear to be universally present in all forms of matter, it has led naturally to the belief that the atoms themselves are structures, or assemblages of electrons grouped in different ways and in motion. It is not sufficient that there should be merely these electrons in the atoms but something else having a charge of positive electricity, because the atoms would otherwise all be negatively charged. The fact that the large majority of matter is in the neutral state without electrical charge indicates that the sum of the positive charges must be the same as that of the negative charges. If this were true of each atom, it would be true of the whole mass, but, because it is true of the whole mass, it does not follow that it is true of the individual atoms. This point is, indeed, one of the questions that remains to be settled by further investigations, as to matter in its ordinary condition.

Before proceeding, it seems best to call attention to an apparent contradiction which has been passed without notice. We have just referred to the constancy of weight of the atoms as established, and yet, it has previously been stated that the conservation of matter is no longer accepted as a fact. At first sight these seem to be contradictory statements. The explanation is that the weight of an atom does not change gradually and continuously by a slow secular change, but, that it changes suddenly with a kind of explosive violence, when it changes at all, by giving up some of its electrons, and thereafter it becomes a different kind of atom, called by a different name, and is weighed as such. The weighing process tells us that the weights of atoms of a given class remains the same, but, it does not say that an atom of one class never changes over into one of another class.

The idea that the atoms themselves are structures, each composed of the same kind of material, the positive and negative electrons, assembled in different ways and moving with different velocities, has in itself shed much light upon many things that were formerly incomprehensible. Even without knowing the precise form

of the atomic structures, it is evident that it is entirely possible that some of the arrangements may resemble each other much more closely than others. We understand better how it may be that the chemist has observed certain groups of atoms that closely resemble each other. We are now one step nearer to a partial statement of the problem of the structure of matter. We must ascertain the precise nature of these atomic structures, the location of each electron, its motion and how many there are, both positive and negative. The answer to the question why we desire to know this, or how would a knowledge of this be beneficial constitutes the whole burden of our theme.

Were it not for the fact that the electron carries a definite charge of electricity, we would not be so encouraged to hope for any answer to these questions. But, at the same time that these remarkable discoveries and observations were being made, there has been developed by generations of men, who have devoted their lives to the subject, a theory of electricity and magnetism. It appears as a natural step to apply these theories to the electrical charges carried by the electrons, because these charges

do not appear to be different in character from other charges of electricity on larger pieces of matter, conductors and non-conductors, with which we are well acquainted. There is no strictly logical reason why these electrical theories, which have been developed from observations on gross matter, should be applicable without modification to the individual electrons, but, any discussion of the justification of applying these theories to the electrons is postponed for the present.

The knowledge that the electrons carry electrical charges immediately brings to bear upon our problem the vast amount of knowledge accumulated by the study of electricity. On this account, a brief review of progress in this subject, keeping our viewpoint continually before us, may not be out of place. The tendency has been gradually but surely toward a unification of many kinds of phenomena, which on the surface appear so different in kind that they seemed to have no connection with each other. One of the earliest observations was that of electrical charges on bodies. If two spheres are suspended by insulating fibres, they are observed to attract or repel each other according as their charges

are of the opposite or the same kind. This influence is transmitted in some way across the intervening space between the two spheres. In this respect the force does not differ from that acting between the moon and earth, or the earth and sun. There is no more substantial connection between the two spheres than there is between these heavenly bodies.

Another early observation was that of the attraction and repulsion between the poles of two magnets. Their influence upon each other is transmitted across the intervening space in just as mysterious a fashion as that of the electrical charges, or that of the moon and earth, and yet there seems to be little resemblance in other respects between the electrical charge and a magnet. A connection of a very direct kind was soon discovered. It is revealed when the charge or the magnet is set in motion. The motion of either one of them creates the other, as it were. If a conducting wire is connected between the two conductors previously charged, there occurs automatically a sudden readjustment of the two charges. The sum of the two charges remains the same after connecting the wire as it was before, but the charge on each

conductor generally changes. If one were positive and the other negative of the same amount, the sum is zero, and the conductors appear to be completely discharged when the wire is connected. When the total amount of anything remains fixed, and the parts shift about from place to place, it is natural to think of it, not as something destroyed in one place and created in equal amount in another place, but, as something that moves from the one place to the other. The evident path, by which the charge in one of the conductors may pass to the other conductor, is the connecting wire. That there is something happening in this wire immediately after it is connected between the conductors is shown by two things. The temperature of the wire is raised momentarily, and small pieces of steel in its neighborhood may become permanently magnetized. This magnetism is produced or created by the electrical charge, and, as we shall see, by its motion along the wire.

On the other hand, when a magnet is moved near a metal or conductor of electricity under the proper conditions, similar phenomena are observed to take place in the conductor or wire to those when the wire was connected between

the two charged conductors. Heat is liberated in the conductor, and magnets in the vicinity are similarly affected. Moreover, electrical charges may be created on the conductors by the motion of the magnet. When a conductor exhibits these conditions it is said to carry an electrical current.

The differences between electrical and magnetic observations were so great that different units were employed to measure electrical and magnetic quantities. When two electrical charges at unit distance apart attract each other with a force of unity, each charge is said to be a unit charge. And, when two magnet poles at a unit distance apart attract with a unit force, they are each said to be unit magnet poles. From what has been said above, the electric current appears to be a kind of connecting link between static electricity and magnetism. The amount of the current may be expressed either as depending upon the definition of a unit charge, or upon the definition of a unit magnet pole. In the two cases we obtain a very different number for the measure of the same current, the one in electrostatic units, and the other in electromagnetic units. In other words, the definition of unit charge

really implies the definition of other units, including that of the electric current and of magnetism itself. Similarly, the separate definition of a unit magnet pole really implies the definition of other units, including that of the electric current and of electrical charge itself. And so it has come about, because of the way in which the subjects were developed, that there are now in use two units for measuring each kind of electrical or magnetic quantity. It is as if we sometimes use centimeters and sometimes miles in measuring lengths.

So it becomes necessary to know the ratios of the electrostatic and the magnetic units in measuring any kind of quantity. The object of dwelling upon this subject at some length now appears, when it is stated that it was found that the numerical ratios of the two units for measuring any given quantity, first in electrostatic units, and then in electromagnetic units, is always some power of the number expressing the velocity of light. This is the first intimation that the phenomena of light has any direct connection with electrostatics and magnetism. If this is so, we may then include another great department of knowledge as having a direct bearing

upon our problem, all the phenomena connected with the study of light. This is historically a much older subject than that of electricity as such, but, we now have the suggestion that those who have investigated light in the past were in reality studying electrical phenomena.

III

THIS question was not destined to remain long in doubt. Maxwell's now classical Treatise on Electricity and Magnetism, which appeared in the "seventies," postulated the real existence of a medium, the aether, pervading all space, which is at the same time the vehicle for the transference of electrical and magnetic energy. He supposed that light and radiant heat were nothing more than the transference of energy in the form of a wave motion through this medium, that the medium itself is set into actual motion of some kind, and is capable of storing and giving up again energy. These views led him to develop the electromagnetic theory of light, which, with some modification, is in use at the present time and has proved to be most satisfactory.

This theory led Maxwell to predict that there should exist other electromagnetic waves than those of light or heat, as we know them, transmitted by this same medium, the aether, and, if

so, that they should all travel at the same speed as light waves. For, the velocity with which waves travel in a medium depends upon the properties of the medium itself rather than upon any of the various arrangements by which the waves may be started. As an analogy it may prove helpful to think of the transmission of sound waves, if we are careful not to press the analogy too far. Sound waves in the air travel at the same speed irrespective of the quality of the instrument that starts the waves or the pitch of the tone. But, if we change the properties of the medium, air, by substituting water, or steel or wood, in its place, the velocity of all kinds of sounds is the same in a given medium but very different in another medium. In this way, considering that the medium is the same which transmits light as that which transmits electromagnetic waves in general, Maxwell was led to predict that if ever any electromagnetic waves were discovered and could be measured they would be found to travel at the same speed as light.

Judging by our present standards it seems a long time between the announcement of this prediction and its experimental verification by

Hertz in 1887. This was a period when electrical technique was hardly developed to such a stage that experimentation was possible or at least very easily accomplished. If we were asked to pick out one date that stands out more prominently than others in our acquisition of new knowledge bearing upon the structure of matter, it might be this epoch-making work of Hertz. As we now know, these electromagnetic waves which Hertz measured differ from light waves merely in wavelength or period of vibration and quality. Our range of vision is very limited. The eye can detect waves in the aether when their lengths fall somewhere between about 3300 and 7700×10^{-8} centimeters, but the waves that Hertz measured were meters long. The difficulty was that there was no instrument to take the place of the eye by which the presence of these waves could be detected. It was necessary to discover a detector. The detector that Hertz used was a simple loop of wire with the ends brought near together, each terminating in a metal ball. The distance between the balls was adjustable, so that they might be brought as near together as possible without making actual contact. It was observed that a small electrical

spark would pass between the two balls if the detector were placed in certain positions when the generator of the waves was set in operation. The intensity of the spark varied according to the position of the detector, other things remaining the same. With this crude form of detector it is remarkable that Hertz was able to accomplish what he did. For, by its means, he was able to prove that the speed of these waves is the same as that of light within his limits of error of measurement. He was, moreover, able to reproduce many of the well known phenomena of light, including those of interference.

By producing so called "standing waves," analogous to those in an organ pipe or a stretched string in sound, he measured the wavelengths by moving his detector gradually along the wire, when it was observed that the spark would appear at certain distances and then disappear and reappear at regular intervals of length. These points of disappearance and appearance of the spark corresponded to the nodes and loops of the standing wave, and so the wavelength was measured.

He also made the important observation that these waves were not affected by matter in just

the same way that light waves are. These electrical waves could be transmitted with ease through obstacles that would completely obstruct the passage of light. They were transmitted through a brick wall without apparent change. This was a very novel result, but was not disconcerting because the theory should lead one to expect that these long waves would exhibit very different qualities merely on account of the great difference in wavelength. A difference as great as there is between these waves and light waves has been observed in more recent investigations between electromagnetic waves themselves in the low and high frequency phenomena of alternating currents. These things have a direct bearing upon the problem of the structure of matter, because the structure of the atom determines the behavior of matter toward the passage of waves in the aether through it.

A comparatively large amount of power was required to operate the detector that Hertz used, because its usefulness depended upon the visibility of an electrical spark in the air, and consequently was ill suited to detect the presence of waves at any considerable distance from the source. The invention of more delicate

electrical eyes was imperative before long-distance transmission of these waves could become of practical use. The discovery of any of the fundamental truths of nature is sure to be followed sooner or later by useful practical applications. The history of the development of so-called wireless telegraphy is too recent and well known to require description. From the first Marconi patent in 1896, when it began to be realized by practical men that communication at a distance was possible by means of these same waves that Hertz had studied, the progress of the art to its present proportions has been one series of improvements in details. The chief of these is, perhaps, the electric eye, or detector of electromagnetic waves, which has constantly been increased in sensitivity so as to respond to smaller and smaller amounts of energy. Combining this increased sensitivity with an acute selectivity by tuning, so that the great sensitivity exists only for certain wave-lengths, that of the sending station, has accomplished the present high efficiency of the wireless receiving station.

The important thing to be noticed in this development is that every one of the sensitive de-

tectors depends upon the properties of matter at close range, atomic and molecular phenomena. This is imperative if we are to possess an electrical eye which can detect a minimum amount of received energy, and at the same time be quick and reliable in action. The invention of these detectors was comparatively slowly accomplished because the experimentor is at this point carried to the borderland of darkness, the unknown region in the atomic realm. In the last analysis all our problems, both of a practical and theoretical nature, finally lead us to this same unknown borderland, that state of matter which for us has not yet been reduced to law and order. The history of progress in the production of these detectors of electromagnetic waves offers a good example, which has a parallel in many other utilities. We have discovered and are using every day apparatus whose underlying principles are not clearly understood. How much more efficient use may be made of things we do understand. We can devise the most effective means to a given end when all the elements of the subject are well known.

The original form of detector used by Marconi,

the coherer, consisting of metal filings loosely packed together in a small glass tube, did not prove to be very satisfactory, and was soon supplanted by other forms. Who would have supposed that a steel point gently pressed upon the surface of a crystal could be of any possible use as an electric eye? And yet, had we understood the true action of atoms and molecules of different kinds, we should have been led to select just such a simple device, and could have predicted that some crystals would be good for the purpose and that others would not answer at all, for this is the fact. Several kinds of crystals give good results. Silicon and carborundum are efficient. Until we understand more about the structure of matter it must remain obscure how this simple small point of contact between the steel point and the surface of the crystal affects the flow of current between them, and why other crystals behave so very differently. And yet here is a practical device whose successful operation depends upon the properties of a few molecules near the point of contact.

Another successful form of detector of electromagnetic waves depends upon the very pronounced magnetic properties of iron as distin-

guished from all other materials. What is there peculiar about the iron atom that gives it such a lead over all other forms of atoms in the matter of magnetization? This question has not yet been satisfactorily answered, but we are encouraged to hope that it may be. The same piece of iron by heat treatment may be made to have different magnetic qualities, and yet under the microscope not the slightest difference can be observed in the crystalline structure. It has been mentioned above that the discharge of an electrical condenser through a wire may affect the magnetization of small pieces of steel in the vicinity of the wire. A practical detector has been in wireless service which depends upon this fact. The very small alternating currents gathered by the antennae are capable of changing the magnetic state of a piece of iron, especially when it is highly magnetized. The great sensitivity of the ear, and the telephone receiver to small electrical currents has made it possible to make practical use of these facts. By winding a coil of wire around the piece of iron, whose magnetism is suddenly changed by the received electromagnetic waves, and connecting it to the telephone, an audible sound is produced every

time there is a variation in the magnetism of the iron in the slightest degree.

The last form of detector to which we shall refer is very remarkable in that we know that it depends upon the electrons themselves as carriers of an electrical charge. If a tungsten wire is heated to incandescence in a highly exhausted bulb, it is known to emit electrons in amount depending upon its temperature, and the space all around the wire becomes a conductor of electrical current, whereas, it was the most perfect insulator when the wire was cold. If now another electrode is inserted in the bulb and a battery connected in the circuit between the two electrodes, a current is established in this circuit when the wire is hot, and it is known that the carriers of this current through the bulb are the electrons which are constantly emitted by the hot wire. Since these negatively charged electrons are only moving in one direction away from the hot wire, the current they carry must go in one direction, and so, when the connections of the battery are reversed in the external circuit, no current will flow because these electrons refuse to be driven back again into the wire from which they came.

In this device we have, therefore, a very perfect valve, which as it were closes against current in one direction and opens for that in the opposite direction. This is all that is required for the most efficient kind of a detector, for the small high frequency alternating current gathered by the antennae is separated into two parts, the current flowing in one direction passing over one circuit, and that in the opposite direction possibly over a different circuit, a unidirectional current being produced in each of them. The telephone can respond to these unidirectional currents in a most efficient way, whereas it is entirely silent for the high frequency waves of an alternating current. But what is the source of these electrons that come out of the hot tungsten wire, which make this device of great practical utility? This is a part of the problem of the structure of matter, and this question has not yet received a final answer.

Years before the new art of wireless telegraphy and telephony were developed the art of communication by the electric current over wires had reached an advanced stage. Instruments had become standardized and their appearance familiar. Contrasting these with

the instruments used in wireless transmission, there seems a great gulf fixed. Those familiar with the older instruments and methods did not realize that this new art was producing instruments and methods that are also suitable for use on their wires. By applying wireless instruments to wires Squier discovered that these high-frequency waves may be guided better by the wire than they are without it, and that a much larger proportion of the generated power arrives at the destination than is the case with wireless transmission. He succeeded in transmitting such waves over considerable distances by wires, and this, using the methods of tuning well known in the wireless art, made multiplex telephony an accomplished fact in the older art of wire distribution, which must always have certain natural advantages over wireless distribution.

IV

E have briefly traced a remarkable theoretical and experimental development that had its origin in the electromagnetic theory which postulated the existence of a real medium, the aether, filling space. It is this medium which is the carrier of energy in the form of light, heat and electromagnetic waves, and which also makes possible the attraction between electrical charges and magnets at a distance, and there is good reason to suppose that it is also the medium concerned in transmitting the gravitational forces acting between bodies at a distance.

Waves of all lengths, varying continuously from the very longest electromagnetic waves to the shortest light and ultra-violet waves, have been experimentally studied, with the exception of a certain region where the waves are longer than the longest heat waves and shorter than the shortest waves that have been generated by electrical apparatus. Also, as we shall presently see, this range has been extended to waves that are a thousand times shorter than the short-

est ultra-violet waves heretofore known. The reason why certain regions in this continuous spectrum have not yet been explored is that the means for generating the waves have not been found. To start a wave on its journey in the aether some form of matter has to be employed, and it may be assumed that the proper disposition of matter has not yet been tried for these particular wavelengths.

The fact that matter in some form is a prerequisite for starting or for detecting waves of any length in the aether shows that there is a very close connection between the aether and all forms of matter, and that there can be no complete understanding of matter without a knowledge of the nature of this fundamental connection between the two. An hypothesis as to this connection between them, expressed in mathematical language, is one of the foundations upon which modern electromagnetic theory rests. The history of this theory shows that it has passed through a gradual but natural process of evolution from Maxwell's beginning to the present time, and it would, in the nature of things, be very unnatural to suppose that this evolution process is now entirely complete,

and that a state of finality has been attained. Like many others this theory has proved its great usefulness in ways too numerous to specify, but which make it very improbable that the theory will ever be completely discarded. We may expect rather that it will be enlarged and made more general so as to include those phenomena that now seem to lie outside of its domain. As with any doctrine, the work of the theorist really begins when some new experimental evidence is discovered which cannot be interpreted in terms of existing theories.

Such phenomena have already made their appearance, but we will postpone any mention of them for the present. They show conclusively, however, that some modification in the present theory must be found if these new things are to be included in a more general form of electromagnetic theory. As it appears to the writer, the point where such a change may be expected is in just this fundamental connection above mentioned between the aether and matter. However, to build a new structure upon slightly altered foundations is a most difficult task, and one that must of necessity require a long time before anything perfectly satisfactory is found.

In the meantime the physical world finds itself in a difficult position. It has seemed to some that the foundations have been so shaken that they are compelled to express doubts that there are any such foundations, of the kind, at least, which we had formerly been led to expect from the smooth course of things. Fundamental Physical Principles have been attacked and subjected to a fresh critical examination in the light of the new knowledge, and questions of a seemingly metaphysical nature have been forced upon our attention. It may not be beside the point to consider some of these.

Helmholtz once expounded the view that our perceptions never give us an image of, but at most a message from, the external world. All our conceptions of the external world only reflect our own sensations in the last resort. Is there any reason, therefore, to impose upon our consciousness the existence of an independent "intrinsic Nature"? Without attempting to repeat any of the arguments for or against this view, the conclusion, to which philosophers have agreed, is that it cannot be proven that the image we thus obtain even remotely resembles "real" Nature. But, there is another and

a brighter side to this question, for, the bolder assertion that these impressions represent with absolute fidelity real Nature cannot be in any way refuted. The first step in such a disproof would presuppose the ability to assert anything with certainty concerning real Nature, but this is absolutely excluded.

This illustration forces upon us the conviction that, even in Science, common sense must frequently be our guide. Faith in the existence of a certain reality outside ourselves is very strong. Without it who would ever have advanced physical knowledge to the position in which we find it? It is well sometimes to declare our faith, for this naturally has its influence upon all that is said and done, and, to the end of making the point of view of the writer clearly understood, it may be stated that these lines are written in an abiding faith in the reality of the existence of an aether filling space.

In spite of the apparently overwhelming array of evidence for its real existence supplied by electromagnetic phenomena and theory, real doubts have latterly been raised concerning it. It came about in this way. The theory demands that the velocity of propagation of waves through

the free aether shall be constant, independent of the motion of the source relative to an aether supposed to be fixed in space. It was sought to put this principle to an experimental test, and the attention of many able investigators has been devoted to this end. We shall refer only to the now celebrated experiment of Michelson and Morley. They sought to make use of the great velocity of the earth through space with the idea that measurements of the velocity of light in different directions on the earth's surface would turn out to be different according as the ray of light is in the direction of the earth's motion, at right angles to it or against it. The orbital velocity of the earth compared with that of light is only 20 parts in 186,000, so that great precision in measuring the velocity of light is required before such an experiment could possibly be made conclusive. It was their ability to measure the velocity of light with great precision that induced these experimenters to undertake such an investigation, and they succeeded in demonstrating beyond any doubt that there is no measurable difference in the apparent velocity of light in any direction. They have made it plain that they would certainly have detected

any effect as large as that for which they were seeking, and that the effect is not present is now regarded as an established experimental fact.

This result has been the cause of considerable controversy and much speculation. At first thought it is natural to suppose that they have proved that the hypothesis that led them to make such an experiment is not well founded. This hypothesis is the so-called principle of the constancy of the velocity of light. But to suppose that this is not true does not relieve the situation any, because, if the velocity of light were variable, it is just as difficult to see why it should always vary in such a way as to have all measurements on the earth make it appear as though it is absolutely constant, that is, of course, assuming that the earth is moving through a fixed aether. Several other ways out of the difficulty have been pointed out, but, thus far, it cannot be said that any one of the explanations is the truth. The proposals have all been of such a nature that they cannot be subjected to direct experimental demonstration, or rather they have not been as yet.

The proposal that has received the most atten-

tion is of such a startling and subtle nature that we shall make a brief reference to certain phases of it, the doctrine sometimes called the theory of relativity. Perhaps the chief of these strange conclusions, to which this doctrine has led, is that space and time are not independent of each other, and that there is neither such a thing as absolute length nor absolute time; but that these are merely concepts, entirely dependent upon the position and motion of the particular observer concerned. And thus it comes about that there is neither an absolute unit of length nor of time, and that these keep changing according to the relative motion of the observer. But they are obliged to change in a certain way to accomodate the theory to the observations. The values of the units themselves, in fact, change by just the proper amounts to make the velocities always appear to be the same in the Michelson-Morley experiment whether the light travels in the direction of the earth's motion or at right angles to it. These ideas have been generalized until it is concluded that it is impossible for an observer on the earth, using his own units of measurement, to detect his unaccelerated motion with reference to an aether supposed to be fixed.

This doctrine reminds one forcibly of the first argument cited above, which denies the existence of an "intrinsic Nature" external to ourselves, in that it refers everything to ourselves as the observer, and seeks to discredit the existence of any absolute reality independent of our sensations. So this doctrine refers everything to an observer and denies the existence of a space or time independent of the observer. And, similarly, the same remarks made above in refutation of the doctrine that "our conceptions of the external world only reflect our own sensations in the last resort" seem to be applicable also to this new doctrine. If we admit the actual absolute reality, and independence, of space and time, they must still appear to different observers to be the same as they actually do appear. No undeniable proof of the one or the other position has yet been found, and perhaps, ever will be found. A yawning gulf seems fixed here, and we are impelled as in the former instance to let common-sense be our guide. Faith in the reality of an absolute space and time is very strong.

Another strange conclusion, which this doctrine of relativity involves, is that "there is no

such thing as the absolute simultaneity of events happening at different places." An illustration usually given to make this clear is that of the "clocks." Suppose that several observers wish to set their clocks to register the same time. Let some central station send a wireless signal to several stations that are, say, at the same distance from the central station, but in different directions. After registering the signal each station supposes that his time is then the same as that at the central or any of the other stations. But, let an observer on a different system, say on the sun, look at these clocks. They will appear to him not to register the same time, for he sees the earth in motion relative to the sun, and notes that the signal from the central station when setting the clocks arrived earlier at those stations that are behind, and later at those that are in front in the direction of the earth's motion, because the former were advancing to meet the signal waves, and the latter were retreating before them. If, now, events happen at each of the stations that appear to the observers on the earth to register the same time on all the clocks, and thus appear to be simultaneous to them, these same events will appear to the observer

on the sun to happen at different times because the clocks to him are not alike.

There are other modes of viewing this question, which the writer has never seen emphasized anywhere, but which seem worth recording. The observers on the earth, being intelligent, recognize the possible difficulties that an observer on the sun or any other system may experience in observing their clocks, and they begin to suspect that, after all, the time was different required to transmit the wireless signal from the central station to the different outlying stations, even though it may not have appeared so to them. So they begin to suspect that their clocks are not alike. The remedy which suggests itself is to have each observer actually bring his clock to the central station, set his clock and return with some asssurance that his time is the same as that of all the other clocks. It seems perfectly legitimate to assume that clocks can be made which will run at a uniform rate, depending, perhaps, upon certain properties of matter, and also that these clocks can be transported from place to place, and, moreover, that there is no place in the whole universe to which we cannot imagine the clocks to be transported.

No observer at any distance from another clock can tell the time by the distant clock, because he is always uncertain how much allowance to make for the time required to get the information, which must always remain an unknown quantity. The only way he can set his clock by the distant clock is to make the journey to it, that is, to reduce the distance between the clocks to zero for the purpose of comparison, and then return again with his clock. He then has some assurance that his clock is in absolute agreement with the distant clock, no matter what the difference in the indicated time appears to him to be from his distant station. Similarly, any number of other observers may carry their clocks for comparison to the central or any other station which has already been compared with the original clock, and return again to their respective places in the same system, or any other system, which may be moving in any possible manner with respect to each other. Each will feel confident that he then has the same unit of time as any of the other observers, namely, the absolute time.

If events happen at different places they may, then, be defined as simultaneous if the clock,

at the exact place where the event happens, registers precisely the same time as is registered by all the other clocks, which are in the places where the events occur. That these events are simultaneous, however, according to our definition of simultaneity, can be told by all the observers at a distance, no matter on what system they may be, provided they can see the permanent record of the events made by the distant clocks, say like that on a chronograph. The transmission of such intelligence as this is a matter independent of time. The journey of the messenger may be long or short without affecting the result.

This definition of absolute time is accomplished, as it were, by eliminating space from consideration, which is done by the necessity for always bringing the clocks together to a zero distance apart for comparison. The mere fact of being able to eliminate space, and still retain a conception of absolute time seems almost to establish the independence of space and time. Why the matter of time should be involved with, or have anything to do with, the time required by an observer to get information concerning the time when an event happens, and also with the posi-

tions in space and the motion of the observers is not at all apparent.

The answer of those who advocate the relativity theory to these suggestions is that there is no such thing as a uniform rate, that we cannot be possessed of any such clocks. That any clock when set in motion changes its rate, and would have a different rate if transported to a different system which is in motion relative to the first system. That all these clocks, though they may be universally distributed everywhere, really register the time of but a single system. For, had we started with a different clock as a standard in some other system, the unit of time would have been different. The question, however, is involved with the definition of a "uniform rate." Since the clocks of any system may be brought to the same point for comparison, the relative rates of the two clocks may be compared provided they are both uniform, and hence one unit of time may serve for all. But, if there is no such thing as a uniform rate comparison would be impossible. Until there is a very definite proof of these very strange ideas one is compelled to assert his common sense and his faith in much the same way as in the

theory of an "intrinsic Nature" external to ourselves.

Although the theory of relativity has received the most attention, we are not forced to accept it as the only possible way out of the difficulties presented by the Michelson-Morley and similar experiments. It cannot be said that there is any explanation of these experiments that is more free from difficulties than the relativity theory, or that is more amenable to experimental proof.

It has been suggested that the great mass of the earth carries the aether within it along with it. If this were so, it would explain the fact that the velocity of light is the same in any direction on the earth's surface. This obvious explanation has, of course, been considered, and the prevailing opinion is against it. Still, it is possible that it may be revived sometime when there is a more complete understanding of the structure of matter. When light waves pass through transparent matter, the velocity inside the matter is always less than the velocity in the free aether. The aether itself within the matter is modified by the presence of the matter. This is the cause of the bending of a ray of light

when passing through a prism, refraction it is called. The fact that the aether in the presence of matter can be modified at all has suggested that, in the presence of a great mass like the earth, this influence may possibly extend to some distance above the earth's surface. Rose-Innes has suggested this as another way to explain the facts. He supposed that such a modified aether would give different velocities of light according to the direction of motion of the modifier through it, namely the earth, and in such a manner that the velocity would appear the same in all directions. Scientists have been reluctant to adopt this view of the aether for one reason because it seems to require a structure for the aether somewhat analogous to that for matter, a kind of atomic structure, for which there is as yet no good evidence.

They have also been reluctant to adopt the view that the aether is carried bodily along with the earth in its orbital motion for a number of reasons. It has been found that the mass of an electron is probably entirely of an electrical nature. Its mass increases with its velocity, almost not at all for velocities less than, say, 1–10th of the velocity of light, and very rapidly

as its velocity approaches that of light. The thought here is that the electron itself is merely a piece of the aether in motion, so that, if the great volume of the aether within the earth is set in motion along with it, the increase in its mass ought to be so great as to prohibit any such view. There is a grave defect in this reasoning, however. A simple translatory motion of the aether may not be sufficient to confer mass upon it. The kind of motion must be taken into the account. If the electron is merely aether in motion it certainly is not simple translatory motion. It must be circulatory motion if any. Translatory motion of the aether along with the earth may not confer any mass upon it.

Lodge regards the non-disturbance of the aether by moving matter as established by the experiments conducted by him. That is to say, there is no viscosity, and the moving matter does not drag the aether in its immediate neighborhood along with it.

From what has been said it is clear that there is at present no entirely satisfactory explanation of the Michelson-Morley experiment. If we adopt the theory of relativity in its entirety with all its perplexing conclusions, as many have

done, we are asked to believe that there is no aether, because its conclusions are not affected by the supposed existence of an aether. Hence, why assume that there is any? Perhaps, this conclusion, more than any other single one, forces us to raise the question that, after all, they have been reasoning in a circle, and one so perfect and well united that we are not able to pick a flaw in it. For, the notion of action at a distance through "empty space" is particularly difficult to accept. Let us now pass to a consideration of certain other phases of the problem of the structure of matter.

V

DISCOVERY that has a direct bearing upon the structure of matter was made by Röntgen in 1895. Practical applications of the X-rays, as they are now called, to surgery are too well known to require comment. This is another instance where practical use has been made of a discovery before its theoretical nature is understood, as the very name "X-rays" implies. The apparatus required to produce these rays is not difficult to construct. In fact, almost every physical laboratory had in its possession all the apparatus required before Röntgen described how to use it. As soon as he did so, the world began taking X-ray photographs. The author distinctly remembers taking from its case at this time one of the standard Crookes tubes, exciting it by means of an induction coil, and obtaining very satisfactory photographs of the bones of the hand and wrist. The vacuum in such a tube has to be higher than that in an ordinary Geissler tube. Instead of glowing

throughout its whole mass as in the Geissler tube, there appears a luminous stream of rays issuing in a straight line from one of the electrodes. If this luminous stream is allowed to impinge upon a metal plate somewhere in its path, this plate becomes the source, in some mysterious manner, of a secondary radiation that possesses very different properties from ordinary light.

It was not until 1912, seventeen years after their discovery, that the true nature of these X-rays became known. There had been much speculation as to their nature, and it had been predicted that they would turn out to be another form of electromagnetic waves in the aether, the same medium that transmits light and heat, the difference being merely in the frequency and length of the waves. It was suggested that these waves were very much shorter than light waves, and so they have since turned out to be, but experimental proof was then lacking.

The common way of analyzing light by means of a "diffraction grating" would not answer at all for these X-rays. Such a grating is made by ruling with a diamond point a large number of parallel lines, either on glass or speculum metal, very close together, from ten to forty

thousand lines to the inch. When this is held in the sunlight several colored spectra appear, having much the same look as when sunlight is refracted by a prism. Different colors are diffracted at different angles by the same grating, and the same color is diffracted at different angles by different gratings, those having different spacing of the rulings. The relation between the angle at which a particular color will be diffracted and the spacing of the rulings is a simple well known quantity, and this angle can be predicted if the wavelength of the light is known. This relation shows that, if the wavelength is very short, compared to the spacing of the rulings, the angle of diffraction would not be appreciable, and the grating, therefore, would show no apparent effect. It was very evident that it would not be practicable to rule lines close enough together to produce any effect, if the wavelengths were really as short as had been surmised.

This led Prof. Laue to imagine that possibly the regular spacing of the planes of atoms in a crystal might be of the right order of magnitude for the distances between the rulings of a grating, and, if so, it would be just possible that a diffrac-

tion effect could be produced by passing X-rays through a crystal. He was eminently successful in the experimental confirmation of these ideas. In collaboration with Friedrich and Knipping, photographs were produced that showed conclusively the effects of the diffraction of the X-rays. They obtained beautiful geometrical arrangements of light and dark spots on the photographs, which were interpreted in a skillful manner by Prof. Laue, who showed that their arrangement is exactly what should be expected, if the atoms in the crystal were arranged in a definite fashion. And this arrangement of the atoms in the crystal was definitely ascertained by him for certain crystals by taking several photographs with the crystal in different positions.

The importance of this discovery, as regards the structure of matter, is not likely to be overestimated. The world showed in a very short time that it fully appreciated the meaning of it. It would be difficult to cite another instance in modern times, where developments have been more rapid, and where improvements on the original experiment have followed so soon. The appearance of the work upon this subject in 1915, only three years after the discovery,

by W. H. and W. L. Bragg on "X-rays and Crystal Structure" shows what can be done in three years time, in a period when the world is devoting its best efforts to this kind of constructive work. It is not reasonable to assume that the significance of these things can be apprehended at once, and we shall devote some space to details.

In a crystal of rocksalt (Na Cl), for example, it has been proven that the atoms are arranged in the form of a "cubic lattice." Imagine a single atom placed at each of the eight corners of a cube. The experiment tells us nothing about the actual size of the atoms, but merely the location of the centers. Now extend the cube in all directions by adding similar cubes, and we have a succession of equally spaced planes of atoms, the spacing being equal to the edge of the original cube. Each of these planes contains atoms arranged in elementary squares, the size of the face of the original cube. If we look at this lattice in any one of the three directions, parallel to the three sides of the original cube, the planes appear to be alike, composed of similar squares. In each plane, however, all the atoms are not of the same kind, one half

of them being sodium, and the other half chlorine. In every line, parallel to the edges of the original cube, they alternate in kind, first a sodium and then a chlorine atom.

Since we know the masses of the sodium and the chlorine atoms, it would be easy to calculate the total mass of a cubic centimeter of rocksalt, were the length of the edge of this elementary cube known. But, the mass of a cubic centimeter of rocksalt is equal to its density, 2.17; hence, the calculation may be made the other way about, and the edge of the elementary cube found from the density. It comes out in this way 2.814×10^{-8} cm. This is, then, the distance between the planes of atoms in the crystal, which may be used for the X-rays just as a grating is used for light waves, namely, to produce a spectrum. A grating with 40,000 lines per inch has a spacing of 0.635×10^{-4} centimeters, which is about as close as lines can be ruled mechanically on metal. This spacing is 2250 times greater than the spacing between the planes of atoms in rock salt, 2.814×10^{-8} cm. just calculated.

There is a simple relation between the spacing of the rulings of a grating and the angle by which

any particular wavelength of light is deflected by it, as above explained. Hence, if an X-ray spectrum line is observed to fall at a definite measureable angle with the face of the crystal, we may then find the wavelength and frequency of the X-rays causing the spectrum line, in terms of the known spacing of the planes of atoms and the measured angle of diffraction. If the source of the X-rays is a bulb containing a platinum antikathode, the spectrum thus obtained is characteristic of the metal platinum. There is usually some general radiation at all angles, but at certain critical angles the radiation is very much stronger than it is for an angle either slightly greater than or less than this critical angle. The radiation energy curve rises sharply to a maximum at certain fixed angles. These particular wavelengths are the characteristic X-radiation from platinum. Such radiation is always the same if a platinum bulb is used, irrespective of the kind of crystal, or the particular face of the crystal, which is used merely as a grating to analyze the radiation, namely, that from platinum.

If potassium chloride (K Cl) is used instead of sodium chloride to analyze the radiation from

a platinum bulb, the spacing of the planes is different, and hence, the angle where this same characteristic platinum radiation falls is different. But, wherever it falls, it has the same wavelength. So the process may be reversed, and the spacing of the planes in the crystal K Cl may be found in terms of the known characteristic radiation from platinum, and the observed new angle. When this is done, the spacing thus found is in agreement with the spacing calculated from the density of K Cl, assuming that there is a single atom at each point of the cubic lattice, as is the case in rocksalt, the potassium now taking the place of the sodium.

Having once determined the wavelength of the characteristic radiation from platinum, or any other substance used as a source of radiation, it is evident that we have here a means of measuring the spacings of the planes of atoms in any crystal in terms of this known wavelength. One of the principal wavelengths from platinum is 1.10×10^{-8} centimeters, corresponding to a frequency of 2.727×10^{18}. This apparatus then serves as a delicate measuring instrument for very small lengths. It is by this means that the facts concerning the arrangement of the

atoms in crystals thus far obtained have been learned.

The difficulties of applying the method are evidently greatly multiplied by the complexity of structure of the crystal. For, although the analogy to a simple grating is useful for explaining the nature of the phenomena, yet, the various planes of atoms in a crystal are not always like the uniform lines ruled on a grating. It should rather be compared to a grating on which some lines are deeply cut and others lightly, and again, to a grating in which certain rulings may be omitted at regular intervals. The theory of the behavior of such gratings becomes more complex the more irregular they are. Consider the rocksalt crystal once more. All the planes parallel to the cube faces are alike, containing equal numbers of sodium and chlorine atoms; but, suppose the crystal is turned so that the diagonal of the cube is vertical, instead of the cube faces as before. If we now cut the cube by a horizontal plane, perpendicular to this diagonal through its center, we have a section which is a regular hexagon, and all the atoms in this plane are arranged in equilateral triangles instead of squares. Moreover, all the atoms

in this plane are of the same kind, and those in the next plane, up or down, are of the opposite kind, being either all sodium or all chlorine atoms, these planes again being spaced at regular intervals, but different from the other planes. This would behave like a grating having a deep cut alternating with a light cut at equal intervals, because the chlorine are heavier than the sodium atoms, and the spectrum should and does correspond to that expected from just such a grating.

The wavelengths of the principal yellow D lines of sodium light are nearly $5900.\times10^{-8}$ centimeters, corresponding to a frequency of nearly 5.1×10^{14} waves per second. The wavelength of certain characteristic X-rays from platinum, as above described, is only 1.10×10^{-8} cm., and the frequency about 2.73×10^{18} waves per second. This X-ray frequency is 5360 times greater, and the wavelength the same number of times smaller, than that of sodium light. This is in agreement with the prediction that the X-rays were probably waves of very short length; but, this discovery of Laue was the means of experimentally verifying this prediction. This is the first actual proof that there is something in the atoms that is capable of vibrat-

ing periodically at a rate far greater than the most rapid ultra-violet vibrations heretofore known. How is it possible that the same little atom can give out or respond to vibrations varying through so great a range as this? The theory of the constitution of atoms, as made up of electrons, throws some light upon this question as we shall see, but, it must be said that no complete explanation of the very large number of the characteristic periods of vibration of a given atom has yet been found.

The light spectrum alone of a carbon or an iron atom shows thousands of characteristic periods. The calculation of these, on any theory of atomic structure, is a most involved operation, and we shall probably have to rest content for some time to come with being able to show that there is some probability that we should obtain these characteristic periods, if it were practicable to make the calculations. Although as much time and study has probably been devoted to spectrum analysis experimentally as to any other one special topic in physics, it seems as if the results, of a fundamental character connected with atomic structure, are very meager, out of proportion to the work that has been done.

The reason for this does not seem far to seek. The phenomena of light spectra are probably connected with secondary vibrations of a complicated kind taking place within the atom, and, consequently, such observations should not be expected to fall into line easily with any theory of atomic structure. They must await their turn, after the primary phenomena are discovered and fully understood.

The X-ray spectra are a step nearer to these primary phenomena, and we may hope, therefore, to be able to arrive at a first approximation to the structure of the atom through a study of these spectra rather than by optical spectra. One great step has already been taken by means of these spectra, which shows clearly that we are here dealing with a primary phenomenon, intimately connected with atomic structure. This work was carried out by Moseley, who made a careful comparative study of the characteristic X-ray spectra obtained from many different chemical elements. He found that the characteristic wavelengths of many different elements resembled each other, as to the spacing of the spectrum lines, but, that, as the atomic weights are greater and greater, the lines are

shifted in a regular manner from element to element, showing progressively shorter and shorter wavelengths and higher frequencies. He plotted the square root of these frequencies for each element from aluminum, atomic weight 27.1, to gold, 197.2, and arranged the elements in the order of increasing frequencies. The result was most important in that the points thus charted lie upon nearly perfect straight lines. They really lie upon smooth curves having a very slight curvature. This same regularity was not found for the elements sodium and magnesium which are lighter than aluminum, and there was an indication of irregularities for the lighter elements. The atoms were then numbered in the order in which these spectra placed them to give these straight lines. There seemed good reasons to begin the numbering with aluminum as 13, and this gives gold the number 79. Each of the intervening numbers but three correspond to one of the known elements, and Moseley predicted that there exist but three more elements between aluminum and gold yet to be discovered. The spectrum of these three unknown elements is thus known in advance of their discovery, and it now seems likely that the

X-ray spectrum will finally be the means leading to their discovery.

This is the first time that any properties whatever of the chemical elements have exhibited any regular succession or progression from element to element, which shows beyond a doubt that there exists a relation between them of a much more fundamental character than any yet obtained. The weights of atoms show a progression from element to element in a similar manner, but the weights are not at all exact multiples of the weight of a hydrogen atom, that is to say, if the atomic weights are charted for the elements in the order of their succession, the points so plotted do not fall upon a smooth curve, but are quite irregular, showing only a general progression in the direction of an average curve. Heretofore, the atomic weight has been regarded as the most fundamental characteristic we possessed of an atom, but, now the atomic number has become the more important thing. Except in the cases of argon, cobalt and tellurium the order of the elements as determined by the X-ray spectrum is the same as the order determined by atomic weights, but, the former is now the preferred order of progression of the elements.

VI

IT is proposed to give an account here of some applications of electro-magnetic theory to matter in its ordinary steady state at the absolute zero of temperature. This includes the structure of crystals, from which we have learned something about the atoms themselves, thanks to the fact that the forms of space lattice in many crystals have been determined experimentally by the X-rays. But, in fairness to the reader, he is cautioned that the author is obliged in this section to draw upon the materials from his own theoretical investigations. We shall first show that it is very probable that the force of gravitational attraction is due primarily to the mechanical force between the revolving electrons within the atoms of distant bodies acting upon each other, and that this force can be calculated. To approach the subject intelligently let us consider some fundamental conceptions of atomic structure.

There is a consensus of opinion that an atom in its neutral steady state consists of equal amounts of positive and negative electrical charges, and

that the positive acts as a binder to hold the negative electrons together, and keep them from escaping; for, the negative electrons repel each other strongly and require the presence of the positive electricity to overcome this repulsion. It is agreed that the positive electricity determines the position of the center of the atom, and is at comparative rest; that the negative electrons are in rapid revolution around the center so determined; and, that the hydrogen atom contains but a single negative electron. There is a difference of opinion as to the exact number of electrons in other kinds of atoms.

One of the principal results of electromagnetic theory is that an expression for the mechanical force due to one moving charge acting upon another has been obtained. It is the consensus of opinion that these electromagnetic equations for the mechanical force should be applicable to the charges of the electrons in the atoms, when *in their steady state* not radiating energy, as in crystals, for example, at the absolute zero of temperature. Such equations give the force acting upon one of the charges due to the other at a single instant of time only. It is not easy to convey by words an adequate idea of the force

expressed by these vector equations. If the charges are at rest, the force is merely an electrostatic repulsion acting in the line joining them; but, when they are set in motion, a magnetic field is created by this motion, which alters the simple expression applying to the state of rest, by introducing terms that depend upon the velocities of the charges. The surprising result is obtained that the force acting upon one of the charges is no longer in the direction of the line joining the two charges. Before this effect of the motion of the charges is very appreciable, however, it must be very rapid, say 1–100th of the velocity of light or greater.

Due to this circumstance, these formulae cannot be tested experimentally in the same way that many theoretical results may be tested. We cannot set two charges in motion at any such rate and measure experimentally the effect that one has upon the other. The required velocity is too great. To be sure, we may consider that an electric current represents charges in motion; but, this only tests one phase of the matter, because the current must flow in closed circuits, and we get at best an average effect of many charges in motion.

Rowland charged the circumference of a wheel, and revolved it at as rapid a rate as possible, to see whether a magnetic field would be produced by the moving charges. He found that it was so produced, and in the same amount as the theory predicted, within his error of measurement. But, the effect was extremely small, and at best this only verified a very small part of the statements contained in the expression for the mechanical force in the electromagnetic theory. We can hardly hope for any direct experimental tests of these theoretical forces in the way that we should like to make them, and must, therefore, depend upon indirect tests. These are not usually as satisfactory, but it is the only way. This explanation has been given here to show that we may regard the present forms of electromagnetic theory applying to moving charges as tentative and subject to possible correction, if a modified form of the theory proves to be more in harmony with experimental facts.

Let us next consider the mechanical action of one moving electron upon another. The simplest form of a closed orbit is the circle. If the orbits of the electrons in the atoms were ellipses or more complicated curves, this would simply add to the

complications of the calculations. The effects that are present when the orbits are circular would still remain when the orbits are elliptical, but, other effects would also appear. For theoretical applications we require the simplest possible conditions, and we are interested to know the results that follow from a supposed circular form of orbit, resting assured that these and other effects would be combined were the form of the orbit more complicated. So, in the ultimate analysis of the problem, if we desire to know the force with which one atom acts upon another, we must find the average mechanical force that one electron exerts upon another when each is revolving in a circular orbit as the simplest case. The author has solved this problem using as a basis two different forms of electromagnetic theory. First, let us consider the results of the application of the most recent, or Lorentz, form of this theory.

As the two electrons revolve in their respective circular orbits, the force that one exerts upon the other is a variable quantity both as to direction and magnitude; but, considering each electron as a component part of two different atoms, the atoms would only be affected by the average

force due to the electrons taken over a large number of revolutions. In taking this average, the only way as yet found to get the result is to express the whole force as the sum of an infinite series of terms. This series is in terms of the inverse powers of the distance between the centers of the orbits of the two electrons. To be of any use in determining the force, such a series must be convergent, that is to say, the sum must be a finite quantity, although the number of the terms may be infinite. For example, the sum of the infinite series of numbers 1, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$, $\frac{1}{32}$, etc., is equal to 2. Hence, because the distance between the centers of the two orbits occurs in the denominator of each term, the greater this distance, the smaller is the number of terms required to give a very approximate value of the sum, and the more rapidly convergent is the series. When the distance is very great, the first term of the series is very approximately the same as the sum, and consequently, if we are interested to know these forces at great distances only, we do not have to calculate more than the first term of these series. It is evident also that, as the distance between the centers of the orbits becomes smaller and smaller, more

and more of the terms of the series are required to get an approximate value of the force, and the series is not so rapidly convergent. There is a minimum distance when the series does not converge at all and consequently it cannot be used, but this does not happen so long as the distance between their centers remains many times greater than the radii of the orbits.

In the form of the force series derived from the Lorentz equations, the first term contains the inverse first power of the distance between the centers of the orbits, the second the inverse second power, and third the inverse third power, and so on, all the powers being present. The direction of the force is not in the line joining the centers of the two orbits. But, since we are interested to know the value of the force acting in this direction, that portion of the whole force which acts in this direction is easily found by the principle of the resolution of forces. When this force is resolved in this direction, the first term of the force-series, containing the inverse first power of the distance between the centers of the orbits, disappears, leaving the expression for the force as the sum of a series of terms beginning with the inverse second power, or square,

of the distance, the next term being the inverse third power, and so on. As above stated, the distance may always be taken so great that the first term of the series is very approximately the same as the sum. The result is that, at great distances such as apply in astronomical calculations, the average force between the two revolving electrons varies inversely as the square of the distance between them. It is well to emphasize the fact that none of the electrostatic force is included in this result. Electrostatically an atom in the neutral condition, like the majority of atoms in the earth, has no effective charge, because the positive neutralizes the negative. The force calculated above is an attraction depending only upon the motion of the electrons, and would reduce to zero if they should stop moving. These inverse square terms are derived, however, from what is called the electric force in the Lorentz equations, which depends in part upon the velocities of the charges, rather than from the so-called magnetic force.

When such forces as have been calculated for two electrons are summed up for a large number of electrons composing two masses of matter at some distance apart, the nature of the inverse

square law of variation with the distance that holds for the two electrons is not changed by the increase in their numbers. This merely changes the amount, or the magnitude, of the force, but not the law of variation with changing distance. There is no limit to the distance at which these forces should be felt, and the force is, moreover, always an attraction. The calculation says, therefore, that there should be an attraction varying inversely as the square of the distance between two distant bodies, say the moon and the earth. Of course, we know this to be the fact, and we have in this result the first suggestion that possibly the force of gravitation may be accounted for by the revolution of the electrons in the atoms. On this account a more careful analysis of this result has been made, and it may be said that it bears all the ear marks of being the gravitational force save one, and that this one disappears, if we are allowed to introduce a factor proportional to the kinetic energy of motion of the electron itself into certain terms of the Lorentz equations. There is likely to be considerable controversy regarding our right to do this. It is merely stated now that, if we do so, the magnitude of the calculated

force agrees very closely with the force of gravitation, within about 1 %.

Some years ago it was thought that, perhaps, the gravitational attraction between crystals, as being bodies in which the atoms are marshaled in systematic order, might show some differences when they are turned in different directions with respect to each other. This was put to an experimental test by Mackenzie, who measured the gravitational attraction between two crystals of calcspar turned in every possible direction. There was no variation whatever found in the attraction to within about one part in 500, which was about as near as his apparatus would permit him to determine the matter; for, it must be remembered that the absolute value of the attraction between these crystals is a very minute force, requiring the utmost precision to detect it at all. Hence, if the force, due to the motion of the electrons, as above calculated, is of the nature of the gravitational force, there must be some good reason why the attraction between crystals is the same in every direction, provided the distance between their centers remains the same. The nature of the expression for the calculated forces makes it clear that this

should be the case. This is one of the earmarks that gives these forces the right look, as being the origin of the force of gravitation.

In this connection it may be interesting to mention that, in order that this result should come out independent of the orientation of the two crystals, it is necessary that a certain geometrical proposition should be true. It was not known at the time whether it was true or not. The proposition may be stated as follows:

If through any point four lines be drawn, making equal angles each with any other, and, if from a second point, at a distance r *from the first point, four perpendiculars be drawn, one to each of the said four lines, then, the sum of the squares of these perpendiculars is constant for all points at the same distance from the first point.* That is to say, the locus of the second point is the surface of a sphere having the first point as the center. The four lines, in order to make equal angles each with any other, must be drawn parallel to the four medial lines of a regular tetrahedron, or to the four diagonals of a cube. The truth of this as a mathematical proposition has since been established. The instance is mentioned here because it is sometimes just slight indications

that show the way the wind blows. If, in an investigation, we are really drifting toward a fundamental truth, other related truths are apt to appear along the route.

As above mentioned, the one point where the calculated force is in disagreement with the gravitational force is in the magnitude of the attraction. The calculated value comes out more than 10^{31} times too great. This is better than as if it came out 10^{31} times too small, because, in such a case we might attribute the gravitational force to something else which did not enter these equations. But, now, the result says that there ought to be a force present immensely greater than any existing force, so that we know that either one or the other or both of the hypotheses underlying the calculation are wrong. They are but two, namely, that the electrons in the atoms are supposed to revolve in circular orbits at uniform velocity, and that the Lorentz equations for the mechanical force apply to such electrons. Of the two alternatives, it has seemed better to say that the present form of these equations requires modification; for, as above stated, they are purely theoretical results that are not capable of being tested in any

direct manner; and, these calculations that have been made seem to afford one indirect test.

The fact that the calculated force has the right look in so many other ways, in being always an attraction and never a repulsion, and in being independent of the orientation of the axes of a crystal, suggested that, perhaps, a factor of some kind had been omitted from the electromagnetic theory. It was found that a factor, one quarter of the mass of the electron times the square of the velocity of the first electron, in terms of the velocity of light as a unit, when multiplied by these inverse square terms, gave the attraction within 1% of the known gravitational force. The mass of the electron itself, $.9\times10^{-27}$ grams, contains the greater part of the factor. Without this factor the force is an unsymmetrical expression, in which the square of the speed of one of the electrons appears, but not that of the other. The rest of the required factor brings in the square of the speed of the first electron, which is omitted, and the numeric, $\frac{1}{4}$, completing the factor, provides a $\frac{1}{2}$ for each of the squared velocities of the two electrons, thus giving the revised expression that symmetrical appearance which seems required.

Adopting these calculations, as being provisionally the correct interpretation of the force of gravitation, we are then able to write down, in terms of the electrons, the gravitational pull between any two bodies. The force is proportional to the product of the sum of the squares of the velocities of all the electrons in one of the bodies times a similar quantity for the other body, divided by the square of the distance between their centers. If one of these two bodies is the earth, and the other is some small body on the earth's surface, this force is merely the weight of the body. We have, then, the means of writing down the expression for the weight of an atom on the earth's surface. But, the weight of an atom of any kind is a constant quantity. If our indication about gravitation is correct, it follows that the sum of the squares of the velocities of the electrons within any given atom is a constant quantity. This deduction supplies the means for a further test of these ideas, as we shall see in considering crystals. It may be stated here that it is not at variance with any of the known facts, and that this conception has pointed the way out of certain difficulties connected with crystal structure that existed before.

VII

THE force exerted by one revolving electron upon another has also been solved, as above stated, by the use of different electromagnetic equations, those proposed by J. J. Thomson in 1881. These differ from those of Lorentz in that they make no allowance for the finite rate of propagation of the electromagnetic field through the aether, and on this account they are simpler and easier to use. In a certain class of phenomena this omission does not make as much difference as in others.

The resulting force in this case also is obtained in the form of an infinite series, in a similar manner to that with the Lorentz form; but, there is no trace of an inverse first, second or third power term. The series begins with a term containing the inverse fourth power of the distance between the centers of the two orbits. There is here no suggestion of any gravitational term. Curiously enough, when the Lorentz form is modified by the introduction of the factor

which has been described, the first three terms of the force-series become very small as compared with the fourth term, provided the distance between the centers of the orbits is comparable with the known distances between atoms in crystals as determined by the X-rays. This is because these three terms are much reduced by the small factor, whereas, there are parts of the inverse fourth power term that are not affected by the factor: so that, at these distances the series really begins with the fourth power term.

This comparison between the Lorentz and Thomson forms of equations has been given in some detail, because it is found that, when the Lorentz form is modified as indicated above, the two forms become approximately the same, as applied to atoms at close range in the formation of crystals. This affords a still further confirmation that the modification made by introducing this factor is of the right kind. It also gives more assurance that we have obtained a form of equation that may be used with more confidence when applied to the distances concerned in crystals, because the two forms are in agreement here.

Before giving a detailed application of these equations to crystals, let us consider some results of a more general nature that the force equation for *two* electrons revolving in circular orbits shows, which tell some things about the atoms themselves. If there is ever any component of the force that one electron exerts upon the other perpendicular to the plane of the orbit, this plane will be forced to change its position, and the motion cannot, therefore, be a simple uniform circular motion. Such a condition of affairs cannot long continue, because there occurs a radiation of energy due to these irregular accelerations of the electrons, and they must finally settle down into a stable circular motion, having no component of the force perpendicular to the orbit. They cannot, according to the equations, be in this condition unless the planes of the orbits are parallel to each other. They show that there is always a tendency on the part of the one to turn the plane of the other until they become parallel to each other. Hence, if there are two or more electrons describing circular orbits around a common center, as in an atom, they must all lie in the same plane, because their mutual interactions will finally

bring them into that condition which has a minimum loss of energy through radiation.

We may picture an atom, therefore, as a collection of electrons revolving in the same plane around a common center determined by the positive charge. The interaction of these electrons causes them to arrange themselves in a system of concentric rings, those in any one ring being equally spaced around the circumference, and revolving at the same speed as each of the others in the same ring. Other rings, having different radii, may revolve at a different speed.

These equations, moreover, give a definite reason why these electrons in a ring must revolve at all. They cannot be in stable equilibrium standing still. There is a tangential force upon each electron, due to all the others in the ring, that drives the whole around with a constant linear velocity, and the equations make it possible to calculate this velocity. As the ring speeds up, the driving force reduces in amount until, at a certain critical speed, it vanishes, and the motion then remains constant. If the velocity were increased above this critical value, the force reverses in direction, and retards the speed, bringing it back again to the same critical

speed. This constant speed is, therefore, the stable condition of the ring.

The absolute value of this stable linear velocity depends only upon the *number* of electrons in the ring, and not at all upon the radius of it. For a ring of only four electrons the absolute value must be 0.00846 part, and for a ring of eight 0.012 part of the velocity of light, no matter what the sizes of the orbits are. These calculations have been made with great care, both by means of the Lorentz form of equations, and by these equations as modified by the factor referred to above as required by the gravitational terms, and it is found that these speeds come out the same to a very close degree of approxmation with either form of the equations. There is every reason to think that these values are correct, not only from this circumstance, but also because they give values that are the same as we are led to expect from other considerations.

If an atom is, therefore, a definite fixed arrangement of rings of electrons in rapid revolution, the sum of the squares of the velocities of all the electrons must, according to this, be fixed too, unless the number of electrons in some ring changes. The size of the rings, however,

may change without affecting the speeds, but not the arrangement. A change in the number of electrons in a ring, if it takes place at all, must take place with a kind of explosive violence, because the steady uniform motion must be interrupted in order to make the change. When this happens, the atom really changes over to one of a different kind, having different properties. We have been led to believe that the weight of an atom, as above explained, is proportional to the sum of the squares of these velocities of the electrons composing it; and, now reasons appear why this sum should be constant for a definite arrangement of the electrons in rings. This would make the weight of an atom of a fixed kind constant. The known fact that it is constant, therefore, goes to confirm the calculation that the gravitational attraction is due to the revolution of the electrons in their orbits.

And, again, we may picture an atom as a small system in rapid rotation characterized by an axis of rotation like any rotating body. This fact confers upon the atom a symmetry with respect to a geometrical line, the axis of rotation, which plays a very important role in the be-

havior of atoms at close range. Consider, for example, the nature of the force that one atom must have upon another at a little distance from it. It is evident from what has been said that there is a tendency of the one to turn the axis of rotation of the other atom until it becomes parallel with itself, and, when in this position, there is no further tendency to turn their axes. The calculations also show that the force which one atom exerts upon a second in the line joining their centers (provided the distance between their centers is comparable with the distances between atoms in crystals) depends primarily upon the directions of their axes of rotation. It is evident that this may easily be true from the fact that the atom has an axis of symmetry. This makes it behave differently from a simple spherical body radiating out its influence equally in all directions. And so it happens that, by simply turning the axes of an atom, while keeping its distance from another atom fixed, the force the one exerts upon the other may be varied at will, and changed from an attraction to a repulsion, if we desire. In other words, the force that the one exerts upon the other is not determined by simply specifying the distance between

their centers. It is not a single-valued function but a multivalued function of the distance between them, so that, unless the directions of their axes were specified, it would have no meaning to represent by a single curve the variation of the attraction or the repulsion between two atoms as the distance between them varies.

With this introduction to some of the general properties of atoms, we may now enter upon a more detailed account of the formation of crystals. The X-rays have located the centers of atoms in some of the more simple crystals. If we fix the attention upon a single atom in the crystal, we know that, since the atom is at rest in a fixed position, the total force upon it due to all the surrounding atoms must be zero. Otherwise it would move and not remain in the one place. This statement applies not only to the translational forces that tend to carry it bodily away, but also to the forces that tend to turn its axis of rotation. Moreover, we have seen that the force exerted by any given atom upon it would be very different if its axis were turned in a different direction from that which it has. We cannot hope, therefore, to be able to calculate the translational forces due to the

surrounding atoms until we know the directions of the axes of them all. This looks at first like a hopeless task, to find the directions of the axes of all the atoms; but, fortunately, we have been able to do it merely from the knowledge that each atom tends to turn the axis of any other, so as to become parallel with itself.

It is not easy to give here more than a mere suggestion as to how this has been accomplished. Suppose, for example, that there is an atom located at the four points of a regular tetrahedron (a triangular pyramid having each face an equilateral triangle), and that the axis of rotation of each points toward the center of the tetrahedron. Consider the tendency of the three atoms in the base to turn the axis of the one at the vertex. Each tends to turn this axis into the direction of its own axis. Since there is perfect symmetry, each atom in the base being at the same distance from the vertex, and the angles between their axes being alike, we do not need to know how great this tendency is for a single atom, because it is evident that it is exactly equal to the tendency of any other atom. The three act in different directions, however, and their turning effects may be represented by

drawing three equal lines from the vertex at equal angles of 120° apart in a horizontal plane, that is, in a plane parallel with the base. These three equal lines may be considered as three forces and added as such, to obtain the resultant effect of the three atoms in the base. This resultant is evidently zero for three forces in a plane making equal angles with each other, independent of the magnitude of the force. Hence, the three atoms in the base combined have no tendency to turn the axis of that at the vertex, so that it may remain in the stable position with its axis pointing toward the center of the tetrahedron. The same reasoning applies equally to any one of the four atoms on account of the symmetry of the regular tetrahedron. It is because of this fortunate circumstance of symmetry that we have been able to locate the directions of the axes of the atoms without knowing at all how much tendency the one has to turn another.

If the atoms were of different kinds, it would be necessary to calculate the effect of each independently, and it is probable that the problem would not have been solved were this required. The question suggests itself how will this be ap-

plicable to crystals like rocksalt, for example, containing two different kinds of atoms. It may be remembered from the previous references to rocksalt that there are certain directions in which the planes contain atoms of one kind only, either all sodium or all chlorine. These are the planes perpendicular to the diagonals of the elementary cube. Without models it is not easy to proceed very far in the description of crystals. It may be pointed out, however, that, if we divide the eight atoms at the corners of the elementary cube into two groups of four each, the one being all sodium and the other all chlorine atoms, each set of four forms a regular tetrahedron having a common center also coincident with the center of the cube. They thus form two interpenetrating tetrahedra, the bases of each being parallel to each other and perpendicular to the diagonal of the cube; but, the vertex of the one points upward and the other downward. Without giving detail as to how the result was obtained, it has been found that, if the axes of the atoms in each one of these planes is arranged in the symmetrical order shown in Fig. 1, then the effect of this whole plane of atoms upon any other atom in the crystal either

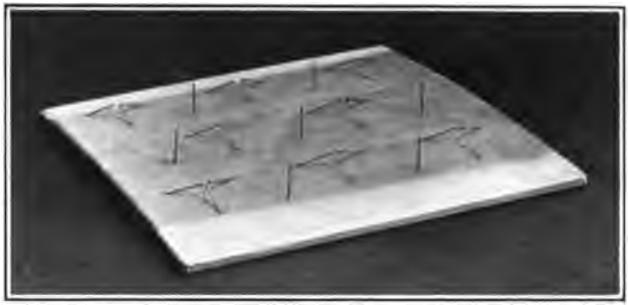


Fig. 1. Model showing the symmetrical arrangement of the directions of the axes of rotation of the atoms in a cubic crystal in all planes perpendicular to any diagonal of the cube.

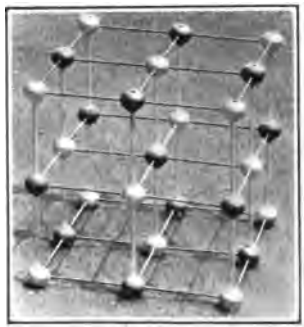


Fig. 2. Rocksalt model.

within or outside this plane, to turn its axis of rotation is zero. That is, this particular arrangement tends to keep the directions of the axes in each plane as they are here shown.

This particular arrangement is the only one that will answer, because of the symmetry and similarity of location of the axes with respect to any one of the four diagonals of the cube. We might have selected any one of the four as the vertical axis, when the arrangement of the axes in the horizontal planes must be alike in any one of the four positions. The arrangement shown in this figure is the only one that will permit of this; for it is evident that some of the atoms in this plane, with the crystal in the original position, also form part of other horizontal planes, when the crystal is turned into any one of the other three positions. There is, therefore, only one arrangement of the atoms that will duplicate the same pattern, when the crystal is turned in these four different positions. An examination of the figure shows that all the atoms are located with their centers at the points of a system of equilateral triangles, and that there are but four different directions of the axes of rotation for all the atoms in the crystal. These

are parallel to the four diagonals of the elementary cube, or, which comes to the same thing, to the four medial lines of a regular tetrahedron. The atoms with axes perpendicular to the plane are arranged in equilateral triangles, twice the size of the elementary triangle. The other axes each point upward toward the center of the regular tetrahedron, which may be imagined to be erected upon the triangle base.

If each plane as a whole has no turning-effect upon any selected atom, then any number of such planes will have none; but the whole crystal, although composed of different kinds of atoms, is made up of such planes, and the sum of the tendencies of all the other atoms in the crystal upon any given one is, therefore, to hold the direction of its axis of rotation in the positions we have found. These remarks apply only to the cubic or isometric system in crystallography; the other systems have not yet been investigated so far as the directions of the axes are concerned. Fig. 2 is the picture of a model showing the positions of the centers of the atoms in a crystal like rocksalt. The black and white balls, representing the atoms, alternate in each direction along the edges of the

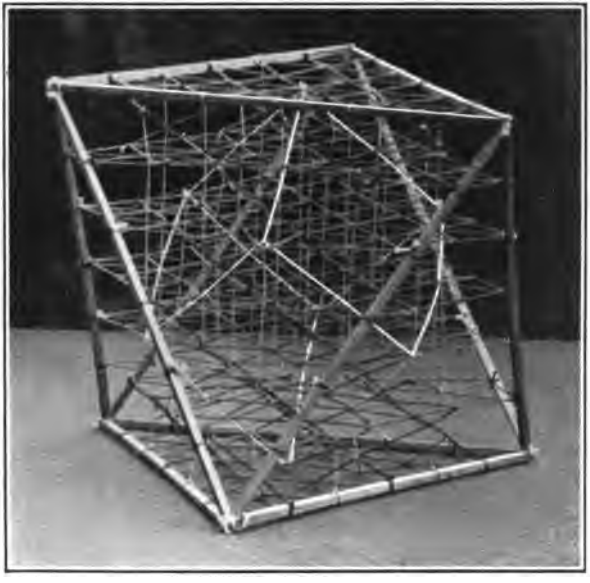


Fig. 3. Model of a crystal of copper.

cube. The hexagon of black balls with the central ball at its center is distinctly visible.

If we now imagine all the black balls to be absent, the only ones that remain are located at the eight corners of the double cube, and in the centers of the six faces of this cube. The atoms are then all of the same kind, and this form of lattice is sometimes called a "face-centered" lattice. It has been found by the X-ray analysis that the metal copper crystallizes in this form of lattice, the copper atom being the only kind present. This is, perhaps, the simplest of all forms of crystals. Fig. 3 is a picture of a model of this form of lattice. This model shows not only the positions of the centers of the atoms, as located by X-ray analysis, but also the directions of the axes of rotation of each atom, located according to the theory above outlined. In the model the directions of the axes are indicated by different colored threads, and the only satisfactory way to comprehend the beautiful symmetry of the whole is to hold the model in the hand and turn it in various directions to observe how the plan repeats itself when turned in the four different directions corresponding to the diagonals of the cube.

For any description of the more complicated forms of space lattice reference must be made to the original papers, but it may be of interest to see the pictures of the models of two other forms belonging to the cubic system in crystallography, namely the diamond, Fig. 4, and fluorspar ($Ca F_2$), Fig. 5.

As above stated, until the directions of the axes of rotation of all the atoms are known, the electromagnetic equations for the translational force acting upon a given atom in the crystal could not very well be applied, but, now we have found these directions. It may be asked what else there is left to be found that we do not already know about the crystal. We know nothing as yet about the size of the atoms as compared with the spaces between the planes in the space lattice, nor about the speed of the electrons in the atoms themselves, nor about the character of the forces that hold the crystal in the rigid shape it preserves. The equation for the translational force that one atom exerts upon another contains only two unknown quantities for each kind of atom in the crystal concerned. These quantities are the distinctive properties of the atoms themselves, which we

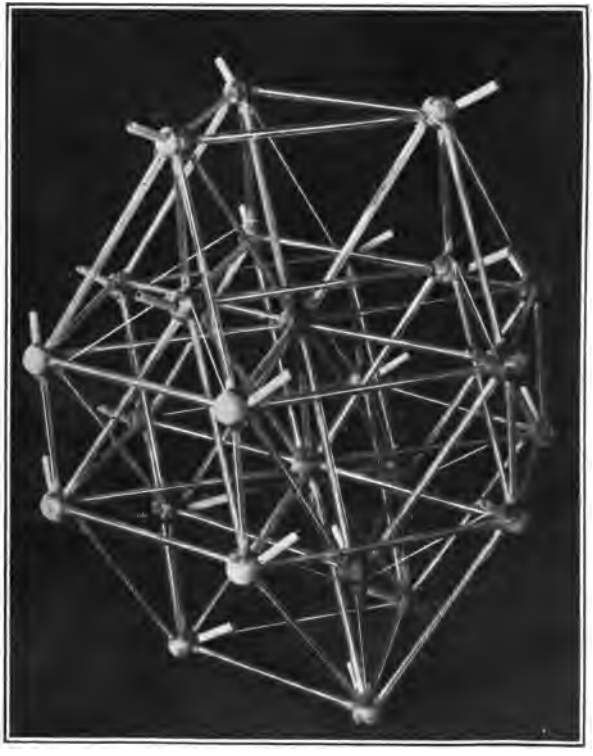


Fig. 4. Diamond Model.

very much desire to know. One of them is the sum of the squares of the radii of the orbits of all the electrons in the atom, and the other is the sum of the products of its radius by its velocity for every electron in the atom. If we knew these quantities, it would give us a very good idea of the average size of the orbits of the electrons in an atom, and the average speeds.

The importance of a correct knowledge of the order of magnitude of these orbits of the electrons cannot very well be overestimated. Until astronomers had obtained an exact knowledge of the distances between bodies, their sizes and masses, and periods of revolution, in the solar system, the correct law governing the motions of the system would not have been found. So with the atoms, if any mistake is made in the order of magnitude of these orbits as great as say one hundred times different from the reality, it gives the atoms very different characteristics, and will delay future progress to adhere to the wrong values.

There has as yet been no other theory of crystal structure proposed, based upon electromagnetic equations, except that developed by

the author. The results of an application of these equations to crystals give only the average values of the frequencies and the radii of the orbits of the electrons, but no values for individual electrons. The calculated average frequencies correspond to the order of magnitude of characteristic X-ray frequencies, and the radii to the order of 10^{-10} centimeters. It is possible, of course, that a small number of electrons circulate in large orbits with smaller frequencies, and that the rest have very much smaller orbits and higher frequencies, so far as we can tell from average values alone.

The distance between the centers of the *nearest* atoms in a diamond, as determined by X-ray analysis, is 1.55×10^{-8} centimeters, one half of this being 0.77×10^{-8} centimeters. This distance may be regarded as established with some approach to certainty. If the radius of the orbit of the outside electrons of the atom is as great as 0.77×10^{-8} centimeters, they begin to overlap in adjacent atoms, although they are not in the same plane, but parallel planes, as may be seen in the diamond model, Fig. 4. If the orbit of any electron is anything like as great as this, the influence of these adjacent electrons upon

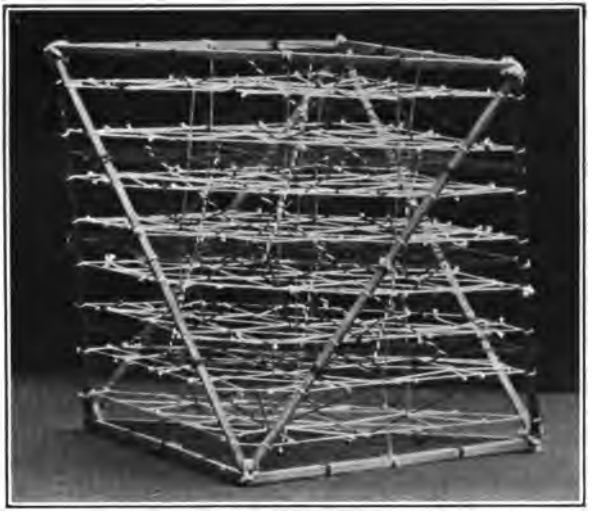


Fig. 5. Model of a crystal of fluorspar, CaF_2. The white planes are fluorine atoms. The darker planes representing calcium atoms are red in the model. By omitting every alternate white plane this becomes the model of a diamond.

each other must of necessity result in a disturbance of the otherwise uniform motion.

This matter is referred to here because there have been very cogent reasons offered by some physicists to the effect that some of the electrons have these larger orbits, and are, so to speak, loosely bound to the central nucleus of the atom, while there are others that have small orbits and are firmly bound to the nucleus. If this is true, then the electromagnetic forces as developed in infinite series cannot be applied to these outside electrons, because, it will be remembered, the series becomes non-convergent, unless the distance between the centers of the atoms is several times as great as the radii of the orbits. In the case supposed the diameter would be about equal to the distance between the atoms, and no calculation has as yet been made that applies to these orbits of large radius. The theory is applicable, however, to the steady states of these electrons, and it remains to be proved by a more comprehensive analysis than is now available that the electromagnetic forces will permit of a stable condition for large orbits.

The atomic theory of Rutherford and Bohr assigns to certain of the electrons these large

orbits, and the frequencies of revolution of these are of the order of optical frequencies, in contrast with X-ray frequencies. Their theory is based upon the "quantum hypothesis," referred to in a subsequent section, and it has met with a wide acceptance. These outside electrons, being loosely bound, are said to be those chiefly concerned in chemical reactions between atoms of the same and of different kinds, that is in combustion, and the well-known chemical "valencies" have received a kind of explanation in terms of them.

Very recently the evidence for their existence has been greatly strengthened by the work of J. Frenkel in calculating the "intrinsic potentials" of, and the Volta contact electromotive forces between metals and non-metals by means of the supposed existence of a small number of electrons having these large orbits. In the way it is done, it is these large orbits only that are responsible for these effects, the small ones being of no avail. A double layer of electrical charge, as it were, is in effect produced over the entire surface of a liquid or solid, simulating an electrical condenser of large capacity. It is this which projects electrons out from hot metals with defi-

nite velocities, thus producing the so-called "thermionic current." Moreover, Frenkel has calculated that the electrical energy per unit of area is the same as the well-known energy of the surface tension of the liquid, and the older method of explaining surface tension seems likely to be supplanted in favor of a method based upon the structure of the atoms. This includes all those familar phenomena of capillarity; why water rises in tubes of small diameter above the level of the water outside; why soap bubbles and raindrops assume a spherical shape, the surface being under great tension like a stretched rubber membrane. According to these ideas the surface is like a charged electrical condenser.

After this digression let us return to a consideration of the method of determining the unknown quantities contained in the force equations referred to above. There are too many unknown quantities to enable us to obtain definite numerical values of these quantities without the help of another relation. For certain reasons that cannot be cited here, some investigators have been led to believe that the electrons in all atoms each have one constant property connected with their motion. It has been

suggested that the product of the radius of its orbit by its velocity in this orbit is a constant for each and every electron. This is a very strange conclusion for which there seems to be no fundamental physical necessity. In the original investigation with crystals this was employed, because there seemed to be nothing better at the time. The hypothesis is sometimes called the "equal angular moment of momentum hypothesis." The use of this hypothesis led to results for certain crystals that were opposed to the experimental results obtained by X-ray analysis, and the hypothesis has, therefore, been abandoned, as having no very good foundation. This theory evidently makes the total angular moment of momentum a constant for any given atom, since the number of electrons is constant for the atom, and according to the theory each contributes the same amount of angular moment of momentum. It was probably this observation, that the average angular moment of momentum is constant for different atoms, that led to the erroneous generalization that each electron contributes the same amount. According to these views, an electron having an orbit of half the radius of another must be moving

with double the actual velocity, and the angular velocity would be four times as great. An atom of this sort would have the inside rings revolving with far greater speeds than the outer rings.

In a later investigation the hypothesis above outlined, obtained from a consideration of the gravitational force between bodies, and particularly as applied to the weight of an atom, which indicates that the sum of the squares of the velocities of the electrons in an atom is constant, has been used. The difficulties previously encountered with the former hypothesis disappear, and, moreover, this new idea shows that there was good reason for the average angular moment of momentum for different atoms to be constant for the heavier elements. It does not give the inside rings of electrons, however, a greater actual velocity than the outside rings, and so does not satisfy the equal moment of momentum hypothesis for the individual electrons at all. The fact that the difficulties encountered before have disappeared by the introduction of the weight equation affords a still further confirmation of this equation. It is an indirect confirmation, to be sure, but we have to

be satisfied with indirect indications in all investigations of such a nature, as pointed out before.

The sum of the squares of the velocities of all the electrons in an atom does not appear as one of the unknown quantities, above mentioned, contained in the force equations; but, it is related to them, and enables us in an approximate way to eliminate one of the unknown quantities mentioned. In a crystal like diamond or copper, which contains but one kind of atom, it would then be possible to find the approximate value of the unknown quantities in absolute measure, if we only knew the constant multiplier, by which the sum of the squares of the velocities must be multiplied to obtain the weight of the carbon or the copper atom. Having once obtained this constant, it will answer for all of the other elements; but, in order to obtain it, it is necessary to know for some particular atom the total number of electrons it contains and their arrangement in rings.

We have chosen the carbon atom for the purpose of determining this constant, because it has the smallest atomic weight and atomic number of any of the atoms that enter the crystals considered. It was stated above that there is no

agreement as to the exact number of electrons in an atom. We will not discuss the matter here. Some place the number at six and others at twelve electrons, and there is a consensus of opinion that the proper number is at or between these two limits. On this account, two different forms of carbon atoms have been assumed for the purpose of finding this constant, and it is probable that the correct values of the quantities are at or between the two limits obtained from the two different forms, and that we do not know them any closer than this. The two results do not differ greatly, however, as to the order of magnitude of the quantities sought.

The first assumption for the carbon atom makes it a ring of four within a ring of eight electrons, twelve in all. It was shown above that the number in the ring determines the absolute velocity of the electrons independent of the radius. Hence, in terms of the velocity of light as a unit of velocity, the velocity of the outside ring of eight is 0.012, and of the inside ring of four 0.00846. The sum of the squares of the velocities for the twelve is then 0.001438, and this divided by the atomic weight of carbon 12, gives the constant 0.0001198, which is sought.

If this constant is multiplied by the atomic weight of any other atom, it gives the sum of the squares of the velocities for that element.

The second assumption for the carbon atom makes it a single ring of six electrons, and the value of the constant comes out 0.00005, a little less than half of the above.

The force equation, when applied to the diamond, gives the radius of the outside ring of eight in the first assumption as 0.792×10^{-10} centimeters, and the average frequency of revolution for all the electrons as 0.764×10^{18} revolutions per second. The second assumption gives the radius of the ring of six as 0.614×10^{-10} centimeters, and the frequency of revolution as 0.778×10^{18}, which is about the same as the average frequency in the case of the first more complex atom. The edge of the elementary tetrahedron in the diamond, as determined by the X-rays, is 2.528×10^{-8} centimeters long. This is 319 times greater than the radius of the outside ring of electrons in the first atom, and 412 times greater than that of the ring in the second atom. In either case, therefore, it is evident that the radius of the orbits of the electrons is a very small distance compared with the

distance between the centers of the atoms in a diamond. The models in Figs. 4 and 2 are, therefore, misleading as to the apparent size of the atoms. The balls would have to be so small, if they were made to scale, that it would be impractical to make the model in the way it is made. There is the same kind of difficulty about making these models of molecules, or crystals, to scale, as there is about making astronomical models and drawings to scale. When it is stated that the distance from the earth to the moon is only 60 times the earth's radius, and from the sun to the earth only 215 times the sun's radius, while the distance between the carbon atoms in a diamond is from 319 to 412 times the radius of the outside ring of electrons, the analogy to astronomical distances is more striking. From this it is evident that by far the greater part of the volume of a crystal is not occupied by the atoms of its elements. We may think of this space in just the same way as we think of the space between the sun and earth. The medium that fills the one is continued right through the most dense kinds of matter.

It is to be noticed also that the frequency of revolution of the electrons in their orbits in the

carbon atom is of the order of magnitude of the characteristic X-ray frequencies rather than optical frequencies, which are as above shown more than a thousand times less. In this connection it may be of interest to state that, at the time these results were obtained in 1912, the discovery of Laue had not yet been announced, and there were no frequencies known at the time that approached anywhere near to the values obtained. It is very doubtful whether these results would have been published, had it not been for the fact that the Laue discovery was made public shortly afterwards. It is not to be inferred from the coincidence of the order of magnitude of these frequencies of revolution with those of the characteristic X-rays that the latter are directly caused by the orbital revolution of the electrons. The one undoubtedly depends upon the other, but in a secondary way rather than as a direct consequence of the orbital periods.

When we have to deal with crystals containing more than one kind of atom, there is another unknown quantity present, which prevents any determination of the unknown properties of the individual atoms from the information derived

from a single crystal. But, fortunately, the same kinds of atoms enter into a number of different crystals. For example, the crystals Na Cl, K Cl and Ag Cl each contain chlorine, and, if the chlorine atom preserves the same properties in passing from one substance to another, we are able, by combining the results from the three crystals, to find the required values for the chlorine atom. In this manner it has been possible to construct a curve for all of the elements, which gives the desired unknown quantities, the sum of the squares of the radii of the orbits of the electrons within the atom, and the product of the radius and the velocity summed up for each electron, as well as the sum of the squares of their velocities. Another curve gives the average frequency of revolution of all the electrons in the atom. These curves are not smooth curves like those of the characteristic X-ray frequencies obtained by Moseley, but they have about the same irregularities as the well known curve of atomic weights.

There is one result of a surprising character concerning the properties of the same kind of atoms as existing in different crystals. While the atomic weight remains the same every time,

that is to say, the sum of the squares of the velocities of the electrons remain the same, yet their radii and the total angular moment of momentum may have different values. These statements apply more particularly to the atoms of oxygen, sulphur, chlorine and bromine, so far as the crystals that have been studied enable us to find out the facts. And, when their radii change for any given atom, the change is always by a definite amount. For example, the sulphur in galena (Pb S) is different from that in either zincblende (Zn S), manganblende (Mn S) or iron pyrites ($Fe S_2$). The sulphur atom in the latter three seems to be of the same kind, but in galena the sum of the squares of the radii are less by the factor $2^{\frac{1}{3}}$. The chlorine in Ag Cl also seems to have the sum of the squares of the radii less in the same proportion, namely the factor $2^{\frac{1}{3}}$, than in Na Cl and K Cl. Similarly, the value for bromine is less in Ag Br than in K Br in the same proportion.

There is no explanation as yet why this occurs, but it is in entire agreement with the ideas that chemists have developed from their observations on the behavior of these atoms. They have come to believe that there are different

kinds of the same kind of atom so to speak. Their atomic weights are the same, but they act differently in different compounds. There may possibly be some closer connection between this property and the valency of an atom, which is not yet completely understood.

VIII

LECTROMAGNETIC theory applied to the atoms in a crystal in their stationary state shows that they are held rigidly in their respective places by the action of the electromagnetic field generated by the constant revolution of the electrons in the atoms. This is combined, however, with a static effect, that is, an effect which would exist just the same if the revolution of the electrons should cease without changing the positions of anything. Although the positive and negative charges are equal and neutralize each other in an atom, yet, this is only *very* approximately true when the atoms are at great distances apart. The size of the atom is then quite negligible, and its effect the same as if all the electrons were at the center of the atom: but, when the distance becomes so small as in crystals that the size of the atom is appreciable, the fact that all the charges in the atom are not located at the same point, namely the center, gives rise to an electrostatic force between

the atoms. The lowest order term in the force series from this cause is the inverse sixth power of the distance. When terms due entirely to the motion of the electrons are also included, the first term to be effective in the force series is the inverse fourth power. This force has the opposite direction from the electrostatic term, and thus, if their values were the same, they would entirely nullify each other and reduce the force to zero if the higher terms in the series are negligible. Of course, since the series is infinite, the even powers only being present, there is also a sixth power term due to the motion of the electrons. This is so small, however, as compared with the sixth power term arising from the electrostatic force, that it does not change the value of the sixth power term in an appreciable degree.

Now, when anything varies as the inverse sixth power of the distance, some distance may be chosen that will make the value of the quantity anything we choose, and similarly for the inverse fourth power term. There is one particular distance, therefore, where the values of the fourth and sixth power terms are equal to each other, and because they are opposite in

direction, the total force at this particular distance is nothing, provided the distance thus found happens to be great enough so that all the higher terms in the infinite series are negligible. When the two atoms are situated at this critical distance from each other, they tend to stay there, and to resist any force that attempts to displace them. If such a force should increase the distance between them, the inverse fourth power term becomes larger because it does not decrease so rapidly with increasing distance as the inverse sixth power term does, and the attractive force will then preponderate and restore the atoms to their original positions after the cause of the disturbance is removed. Had the disturbing force decreased the distance between them, the inverse sixth power term would preponderate, and repel the atoms back again to their original positions after the disturbing force is removed.

This is the reason why crystals are rigid bodies. If any external force should be exerted upon a crystal so as to tend to alter its shape, it would resist such a change of shape; and still more would they resist a mere change in volume without any change in shape; for, every atom would

be compelled to go nearer to its neighbor if it is a compression, and the resistance in such a case is decidedly great because every atom adds its bit to the grand total. If the external forces do not alter the volume, then all of these effects are not simply added together, and the total is not so much.

If we are on the right track, that is, if we have found the true explanation of the rigidity of bodies and their resistance to any change of volume, we should be able to test the matter, because these things have been subjected to experimental measurements. Our theory ought at least to show that we obtain as great effects from these electromagnetic forces as are matters of common observation. Fortunately, we have been able to make some such comparison, and the order of magnitude of the effects is the same as those observed. However, the difficulties of calculation are too great as yet to make it possible to find the resistance that a crystal offers to any change of shape. We have to be satisfied for the present with calculations based upon change in volume only. Such a change may take place in such a way as not to disturb the shape of the space lattice formation of the

crystal. All the angles remain undisturbed, and the only change that takes place is in the absolute dimensions of the elementary cube of the structure. That these forces must be very great is evident from the fact that we commonly think of most liquids and many solids as incompressible substances. Their change in volume is so small for all ordinary pressures that for most purposes it is entirely ignored. There does take place, however, a change in volume with applied pressure. An idea of the small amount of the change may be obtained from the statement that, roughly speaking, a given volume of water is reduced by one part in 21,000 for an increase of pressure of one atmosphere. These changes are so small that it requires great precision to obtain correct experimental values.

It is not feasible to give here the method but merely state the results of some calculations that have been made for certain crystals. In each case the calculated values show that resistance to the applied pressures is somewhat greater than the experimental values indicate, but that the order of magnitude of the effect is about the same. That is, these electromagnetic forces are entirely sufficient to show as great a

resistance to change of volume as actual substances show, and they indicate a greater incompressibility than the measured values.

The experimental measurements that have been made on crystals show a very great variation in their compressibilities, for example, tourmaline is 66 times more incompressible than potassium chloride. The calculated values do not show quite as great variations between different crystals as the measured values indicate. In considering the matter more closely, it seems that the difficulties connected with the experimental determinations have not yet been entirely overcome. Experimentally we cannot press upon the surface of a crystal with another substance having a smooth, hard, continuous surface without any pores, because we have to use some form of matter, and, as we now know, every form whether liquid or solid has its atoms at certain distances from each other. We have to employ a surface with a lattice structure to press upon another lattice structure. By exerting great pressure by means of liquid mercury upon a piece of steel, Bridgeman has shown that, when the steel is broken afterwards, the entire surface of the break is amalgamated with mer-

cury. In other words, the mercury has been forced to penetrate the whole mass of steel. Now, if mercury or any other substance were used to produce the pressure, and the change in volume of the steel were measured on the assumption that none of the substance penetrated into the interior of it, an error would evidently be introduced in the final result, and it would tend to make the compressibility greater, and incompressibility less, than the true value. Moreover, if any error is introduced by an interpenetration of the one substance within the other, its amount would naturally differ widely with different forms of space lattice. This would then account for a greater range among the experimental than the calculated values.

It is now some years since measurements of this character have been made, and a new series of measurements may well be undertaken at the present time. It should be one object to see whether the same results are obtained with a given crystal when using different forms of compressing substance. A solid compressing substance is to be preferred to a liquid because of the fixed character of the space lattice. The thought here is that all liquids may behave more

or less alike on account of the mobility of the atoms. But, the difficulties in using solids may prove insurmountable, for, liquids have the distinct advantage of adapting their shape exactly to that of the substance being compressed.

Electromagnetic theory applied to the atoms *in their steady state* has thus accounted for two of the principal properties of matter in the crystalline form, namely, the reasons why certain forms of space lattice are possible, and the reasons for the almost perfect elasticity of volume. It should be emphasized that only a very small beginning has been made, but it is an entering wedge and gives much encouragement that there will be more to follow. The whole subject of the other classes of crystals than the cubic forms remains to be explored. There are also other properties of crystals that require attention; but, we have probably considered most of the properties that are present under the hypothesis that the atoms are *in their steady state.* In this state the orbits of the electrons are perfect circles, there being no superposed vibrations or motions of any kind present. This is imagined to be the condition of matter at the absolute zero of temperature.

It is well known that heat is a mode of motion of an atomic nature; but, it is not this motion of revolution of the electrons in their orbits that is associated with the energy of heat. This motion remains when the heat has disappeared. As the temperature rises it is believed that another kind of motion is superposed upon the circulatory orbital motion of the electrons. It is yet to be learned exactly what happens when the atoms begin to depart from their steady states and begin to radiate and absorb energy. This introduces us to an entirely new class of phenomena and of a seemingly much more complex nature than those simple conditions that exist when the atoms are in their undisturbed state. This is what was meant above, when it was stated that the theorist demands first of all the simplest possible conditions to enable him to obtain some kind of results that may serve as stepping stones to further progress.

It is profitable, perhaps, to speculate, in advance of more exact knowledge, upon what might happen to atoms of the kind with which we have been dealing, when they are subjected to shocks and disturbances from external causes. It seems probable that, in the case of the crystal starting at

the absolute zero of temperature and being gradually warmed, there will be a motion of some kind of the atoms as a whole about a fixed center, and also that the electrons within will acquire a relative motion with respect to the center of the atom. It does not matter how complicated these motions may be, the total effect of it is to increase the average velocity of the electrons.

We have been led to believe, as stated above, that the gravitational attraction between two bodies depends upon the sum of the squares of the velocities of the electrons. This idea was arrived at by assuming a circular motion of the electrons in their orbits, so it is not logically necessary to be true for any other kind of motion. The extra motion of the electrons, however, produced by the heat, might conceivably be circular motion also, and, if so, we should certainly expect to find an increase in the gravitational constant with increasing temperature. This would not be the case, however, if the positive charge of the atom partook of the same motion as the negative electrons, because the one would neutralize the other. It is, therefore, only the relative motion of the electrons within the atom with respect to the center of the

atom, that is, to the center of the positive charge, that can produce the effect of an increase in the gravitational constant. Moreover, this effect would be likely to be very small for any ordinary change of temperature.

This matter is mentioned here because Shaw, in an elaborate and careful research published in the Philosophical Transactions of the Royal Society in 1916, has detected such a temperature coefficient in the gravitational constant, and its direction is the same as we are led to expect from this theory. Of course it is yet too early to say that this matter has been experimentally established with certainty, but it is interesting to observe that the theory we have set up not only permits of it, but demands it. The chief difficulty is in calculating its amount, to determine whether such a variation ought to be observable for the limited range of temperatures that it is possible to observe. On the other hand, when the coefficient is firmly established experimentally, it should be possible to approximate to the amount of relative motion of the electrons in the atoms per degree of temperature, that is, motion superposed upon the orbital motion.

The temperature effect, just described, requires

as we see that an internal change take place within the atom itself. Several other effects make the same requirements. If we subject a crystal to an electromotive force, or to a magnetomotive force from an outside source, we may rest assured that an internal change takes place within the atoms themselves. Suppose that we first imagine the crystal to be placed in a powerful magnetic field. This field permeates the whole mass and acts upon each individual atom. We may think, if we please, of each atom as a little magnet having its poles in the line of the axis of rotation; for, the revolution of the electrons makes it strongly magnetic. The tendency will then be for each atom to set its axis in the direction of the field. But, let us proceeed a little more carefully; if the atoms are little magnets, why do they not add their effects together and produce a strong magnetic field, the whole crystal thus becoming a magnet? The reason is that the axes of rotation of all the atoms in the crystal, according to the theory above given, are equally divided into four groups, each of which has its axes parallel to one of the four medial lines of a regular tetrahedron. This arrangement makes the magnetic effect of the

total evidently zero. The theory tells us in advance that these axes of all the atoms in the crystal cannot turn bodily around into the one direction of the lines of force of the magnetic field because the directions of their axes are the most critical things about the crystal structure. To revolve the axes in such a manner would mean that the crystal would not be able to hold itself together, and would fly to pieces and disintegrate. We may rest assured, therefore, that the axes do not turn very far because the other physical properties of the crystal are only changed in an imperceptible degree, when the crystal is placed in the magnetic field. There is, however, certainly a tendency to turn these axes in the presence of an external field. The inference is that there is something stronger which opposes the turning of the axes, and a calculation shows that there is. The intensities of the magnetic fields due to the revolution of the electrons in the atoms is far greater than any artificial fields we can produce by any means as yet found. The atoms themselves are already in a field of so great an intensity that the most powerful fields we can bring to bear upon them are insignificant by comparison, and the whole is so nicely balanced that the

total field for the whole crystal is nearly if not quite zero.

The turning effect of the external field ought to be different for each individual ring in the atom. It is very probable, therefore, that different rings may be turned by the action of the field in different amounts, although it is probably a small amount in any case. We have, therefore, come to the conclusion that the internal arrangements in the atom itself have altered slightly, which justifies the opening statement putting magnetic effects in this class of phenomena. If there are any differences at all in the turning moments of the different rings into the direction of the magnetic field, this will cause differences in the magnetic properties of different substances. It may even explain diamagnetism, although this cannot be done directly. All that we can be sure of is that the process is not a very simple one, and that when an atom is turned ever so slightly, it carries with it its powerful magnetic field, thus affecting other surrounding atoms perhaps to a greater extent than the external field. Indeed, though we cannot calculate it, we easily see the possibility of complexity and intricate relations, depending

upon the crystal structure as well as upon the atomic structure.

The very great magnetic permeability of the metal iron, as compared with other elements, has been the subject of much speculation, and has never had a satisfactory explanation. It is certainly not connected with the iron atom alone, unless it be a single one of the several states in which the iron atom is known to exist, because the presence of iron atoms in various chemical compounds of iron does not produce the same effect as the iron in the metal iron. It requires the peculiar combination of the iron atom and the iron space lattice formation to produce the pronounced result. We may see, however, that, when the external field is removed, the forces within the crystal and within the atoms will quickly restore the whole to its original position. Here, again, the peculiarity of iron, when alloyed with carbon and several other elements, in the form of hardened steel, in retaining a large part of its magnetism when the external field is removed, is difficult to comprehend. It seems as if the form of the space lattice must have changed to a slight extent or in some places, and indicates that a form of lattice is possible in which the

atoms do not have their axes in the four directions of the medial lines of the tetrahedron.

Let us next subject the crystal to an external electromotive force. Some crystals admit of a current passing through them, and others will not allow a current to pass at all. We have learned that an electric current means the flow of electrons, and, in those crystals which permit of it, this means that the electrons are passing through the body of the crystal. This subject of conduction through metals has been the subject of much theoretical speculation, and it may be considered to be in an unsettled state at the present time. Some have attributed the whole effect to free electrons which pass between the atoms of the crystal. And others have thought that the electrons pass from atom to atom on their way through, entering the atom for a time, and passing on later. In this latter case the steady state of the atoms is certainly disturbed, and in the former perhaps not so much so; but, it puts this phenomenon of conduction in metals in the class where there are internal changes going on in the atoms themeslves. This is, perhaps, why conduction in metals is still one of the outstanding problems in which the last word has not been

said. It will be remembered in connection with the crystal detector for wireless telegraphy that its operation depends upon the conductivity of the crystal, and especially at the point of contact between the steel needle and the surface of the crystal. This is one of the phenomena that must fall into line with any complete general theory of conduction in crystals.

In writing these lines concerning the very borderland of our knowledge, some of which seems clear and some hazy and indistinct, the author is conscious of laying himself open to criticism. There is a difference in kind even in speculations. Having had good reason to believe, for example, that the gravitational attraction between bodies is proportional to the product of the sum of the squares of the velocities of the electrons within the two bodies, it is reasonable to make all the legitimate deductions from it possible with the object of testing it in every way. This is, in fact, the only way that its truth or falsity can be established. The following deduction from it may seem fanciful, but, it is put forward merely as an interesting deduction from this premise, as giving for the first time the promise of possessing some method of finding what kind

of chemical elements compose the large interior of the globe on which we live. Heretofore, we have only been able to examine the kinds of atoms on the surface or the crust of the earth to a few miles in depth; but, if the principle just mentioned is true, it gives us the means of finding out something about the interior of the earth and other heavenly bodies. The truth of the deduction depends upon that of the premise, but it rings true in the several ways it has been tested already, and also in this way.

The weight equation for an atom on the earth's surface contains only two unknown quantities, one, the sum of the squares of the velocities of the electrons in one atom, and the other, the sum of the squares of the velocities of every electron in the earth. If we select the carbon atom, as has been done above, we can make a fairly accurate guess at the sum of the squares of the velocities. This is one of the two unknown quantities, consequently we may find within the same limits of error the sum of the squares of the velocities of every electron in the earth. The number so determined is of course very large. It is about 21×10^{46} in terms of the velocity of light as a unit. If we divide this by the

total number of electrons in the earth, we ought to obtain the mean square of the velocity for a single electron. Fortunately, we may easily find the total number of electrons in the earth approximately, because one gram of any kind of substance always contains the same number of electrons, namely 6.05×10^{23}. If this is multiplied by the number of grams in the earth, or the mass of the earth expressed in grams, namely 5.984×10^{27}, we obtain the number of electrons in the earth as 36.2×10^{50}, a number which is larger than the above. Dividing the former by the latter gives 0.00005856 as the mean square and 0.00765 as the square root of the mean square velocity for the average electron in the earth.

Now, as has been pointed out above, we know these average velocities for all the different forms of the chemical elements with the same accuracy as we know that for the carbon atom, and it is very remarkable that any figure obtained in this manner from the data involving the whole earth should come within the range of possible velocities for the elements already known. This result in itself goes to increase the probability that there is something well founded in the hypothesis. It will be recollected that the speed

for a ring of four electrons is 0.00846, and for eight 0.012 part of the velocity of light, both of which values are larger than the average obtained above for the earth, namely, 0.00765. The substances on the earth's crust contain atoms on the average that have values considerably in excess of 0.00765. The atoms in the interior must, therefore, have a value less than this to maintain the average. The only kind of atom that has a value for this speed less than this figure is that of hydrogen, which has a probable value of 0.00369. This result then points to hydrogen as being the substance composing the center of the earth, or, at any rate, only the very lightest of the elements.

At first thought this may seem absurd, because hydrogen gas is the very lightest of the known gases at the atmospheric pressure. The average density of the earth is 5.5247, and the density of the surface is considerably less than the average, so that the density of the interior must be considerably in excess of the average. To think of hydrogen having a density of 6 perhaps is difficult, but it is not so difficult when the immense pressure under which it exists at the center of the earth is considered. The perfect volume

elasticity of any crystal, and probably any liquid, as we have seen, will enable the hydrogen to withstand almost any amount of pressure. The distances between the atoms merely decrease without changing the character of the atoms themselves, and this will increase the density almost as far as we please.

The important thing is that a method has been found, which seems likely to yield some information as to the kinds of chemical elements in the interior of the earth. Whether or not it eventually turns out to be hydrogen is not so important, because this will adjust itself when we obtain more accurate values for the unknown quantities involved.

IX

WE have been able to steer our bark up to this point with comparative ease by the help of electromagnetic theory, so long as we have kept in the smooth waters of the *steady state* of atoms that are neither giving up nor receiving energy. But we are now plainly in sight of the turbulent open sea where navigation is difficult if not impossible with our present equipment. It almost seems as if we must turn back and lay the keel of another ship before any voyage can have a successful outcome in such a sea. There is, however, one more subject remaining that admits of a partial understanding from the standpoint of the steady state of atoms. Crystals have been spoken of as molecules, and they may be considered as such built on a pecular and distinctive system of their own. When a chemist speaks of molecules, however, crystals are not the first structures that come into his mind. The number of atoms in the molecules he pictures are comparatively few, too few to form a crystal.

Take, for example, the gas known as methane (CH_4). In this four atoms of hydrogen have entered into partnership with one atom of carbon, and these five atoms form one molecule. They travel about together as one unit, making many excursions at high speed to and fro among the neighboring molecules of the gas, but all the time they adhere to each other with so much persistence that they are not dislodged by the encounters with their neighbors. They may be torn from each other by other means, but, unless these means are supplied, they remain in each other's company for long periods of time.

In a very important part of his subject the chemist is chiefly concerned with the laws of partnership, which not only govern the numbers and kinds of atoms that may unite together in this way to form one unit of molecular structure, but also that govern the spatial configuration of the united whole. That is to say, are the five atoms of the methane molecule lined up in a straight line, or do they form a ring, or is the carbon atom a center about which the four hydrogen atoms group themselves? He should be concerned also with the absolute distances between their centers when the form of the

figure is determined, although it cannot be said that much progress has been made in this direction as yet. He would also like to know the nature of the forces that bind the five atoms into one whole with such success that they remain united even when subjected to considerable disturbance.

It may be objected that there is some question whether we have any right to think of this phenomenon of the molecules as belonging at all to that class where the atoms may be considered in their *steady states*. We may easily think of the temperature of a crystal as being reduced to the absolute zero without disturbing its space lattice formation at all. It still remains a crystal possessing many of its properties just the same. It retains these properties as it is warmed through a considerable range of temperature; but, as the temperature goes on increasing there finally comes a time when the vibratory motion of heat, which is superposed upon the original steady revolution, completely alters the forces that bind it into one unit, and it then disintegrates or vaporizes into the separate atoms.

But the case is different with a gas. The very motion of the molecules as a whole to and fro

is that due to its heat. If we suppose that its temperature is lowered, the motion is reduced too, and, at the absolute zero, of course all this motion must have disappeared. Then the units composing the molecules of necessity come together forming a solid, in which their individuality as molecular structures of the same kind at least is lost or merged into that of the crystalline forms. A little reflection shows that, in the same way as the properties of a crystal remain during some elevation of temperature, so the properties of a molecule may remain for an elevation of temperature. Since all the atoms of the molecule alike partake of the same translatory motion, as it moves about in the gas, the interatomic disturbances may not be so very great. These disturbances are a maximum, no doubt, when two molecules of the gas come close together. If we apply the ideas of the sizes of atoms and the great frequencies of revolution of the electrons already obtained to this matter, it shows that the interval of time that elapses between successive encounters with other molecules is very great compared with the time intervals involved within the atoms. The thought here is that the molecular system goes on its un-

E1 C-H
E2 C-H

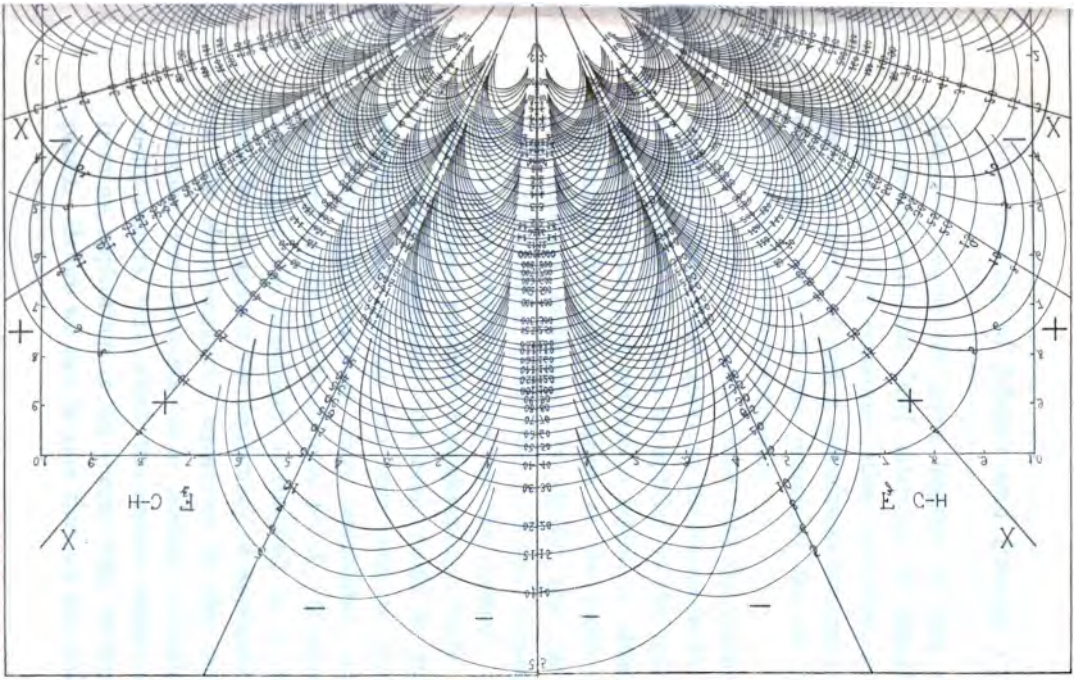


Fig. 7. Field surrounding an atom having twelve electrons, acting upon an atom having but a single electron. To obtain the force in dynes multiply the figures on the curves by 5.31×10^{-6}. To convert distances into centimeters multiply by $.207 \times 10^{-12}$.

disturbed course for great lengths of time as compared with the brief intervals of disturbance when they encounter other molecules, and that the effects of such a disturbance are quickly dissipated before it has proceeded far on its way toward the next encounter.

This is why it is considered that the electromagnetic forces that apply to the atoms in their steady states may also be applied to the molecules of a gas, and perhaps a liquid, to obtain at least a first approximation to the forms of the different molecules. It should also yield some information about the distances between the various atoms making up the molecule as well as their possible configurations. Only a very small beginning has been made in this direction, but, enough has been done to show that the plan contains many possibilities, and no more as yet can be claimed for it. It seems to contain the possibility of enabling us to decide for or against the legitimacy of application of the electromagnetic equations to the case, because the chemists have already obtained many results, with which the results calculated from an application of the theory may be compared. Before we can be sure that we are mak-

ing a fair comparison, however, it is necessary to feel some assurance that the form of the atoms used as a theoretical basis is the correct form. Of course the process might be reversed, and the correct forms of the atoms evolved from the known forms of some molecules. The difficulty here is that not enough is known yet, even in one single instance, of the exact form and dimensions of any one molecule to make such a process successful. Another difficulty is the great labor involved. This difficulty will be surmounted in time provided the process can be shown to be well founded. In the meantime it is necessary to be content with very meager results, and direct those efforts that are made toward proving that the method looks promising.

Another difficulty that increases the labor in the investigation of individual molecules in distinction from crystals is the lack of symmetry of the structures. It will be recollected that it was possible to ascertain the directions of the axes of rotation in a cubic crystal chiefly from its symmetry. The directions of these axes must be known before the equations can be applied. On account of this lack of symmetry there are more unknown quantities to deal with, and the

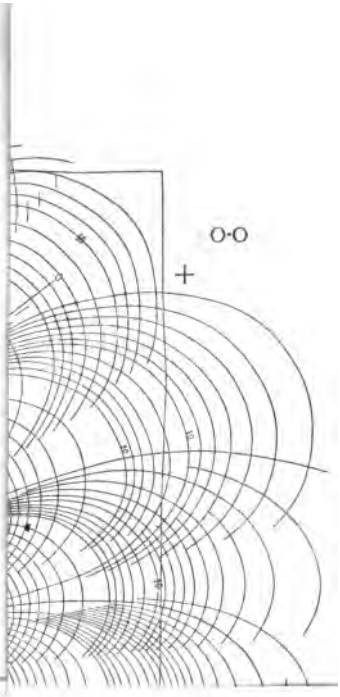
[illegible]

solutions are not so readily obtained as in the case of the crystals described. For the purposes of solving some of these equations by approximation, several graphical charts of the fields of force surrounding certain assumed forms of atoms have been made. These charts are merely the graphical representations of the equations that have been obtained for the mechanical force with which one atom acts upon another. They are only good for the one particular combination of atoms chosen, and for the precise form of such atoms as were assumed. Later information concerning these forms derived from different considerations already require some alterations in them; but, on the hypothesis upon which they were constructed, they are perfectly true representations of the equations. They are reproduced here, in Figs. 6, 7, 8 and 9, on a much reduced scale without any very definite purpose except to reveal the beauty concealed in these equations.

One atom is supposed to be located at the center of the chart with its axis of rotation along the vertical or z-axis, and the other to be placed anywhere on the chart with its axis parallel to that at the center. If this second atom is placed

on one of the curves anywhere on the chart, and then moved along this curve without changing the direction of its axis of rotation, the force that it exerts upon the atom at the center, either in the x- or the z-direction is constant. That is, there are really two sets of curves combined on each chart, the one for the x- and the other for the z-component of the total force. The purpose of the chart is to enable the forces to be read directly when the second atom is located in position. This avoids the necessity for solving the equations each time that a new location is chosen, and affords a short cut to an approximate solution.

Because the two axes of rotation are parallel in the cases assumed for these charts, the figure is symmetrical about the vertical axis, and may be imagined to be revolved about this axis thus generating surfaces of revolution, a single cross-section evidently being all that is required for a complete description of the field in the space surrounding the central atom. If, however, we had assumed that the axis of the second atom was not parallel with that at the center, but retained some other fixed angle as it is moved from place to place, the surfaces are then not


O-O

surfaces of revolution, and there would be a different set of curves in each plane through the vertical axis.

Although a number of forms of molecules have been built up by the use of these charts, this work must all be repeated on account of changes in the numerical values assumed for the atoms, as representing more probable values, and consequently, none of these results will be referred to at this time. The above description has certainly made it clear that patience and perseverance are essential qualities for one who undertakes to enter upon this kind of work, and it emphasizes one of the opening remarks to the effect that trial and error is the only way.

X

SEVERAL allusions have been made in the foregoing paragraphs to difficulties ahead, to a certain class of phenomena which seem impossible to include within any electromagnetic theory. We are face to face with these. They do not appear in the steady states of the atoms considered hitherto, but when there is a transference of energy from place to place; when the motions depart from the steady state and the atoms radiate and absorb energy. The author does not expect to meet with success in presenting these matters, unless, perhaps, a disclaimer at the beginning will satisfy, to the effect that the reader already knows as much about the fundamental causes of these phenomena as any one else.

After the failure of every attempt to explain these things by means of accepted theories Max Planck had the courage to make one of the most radical and bold proposals that has ever been presented to the physical world. He said that,

if we admit that the transference of energy can only take place in definite but very small units, and that the total energy transferred is always an integral multiple of this small unit, an energy quantum, then these phenomena of radiation and transference of energy may be explained in terms of this conception. The idea conveyed by this is that energy too is a quasi atomic phenomenon.

The very great success with which this idea has subsequently met, in explaining many matters in terms of this energy unit, that have not been explained in any other way, has given this constant of nature a claim to have been experimentally established. It is now known as Planck's constant. The chief results may be generalized into a very simple statement, namely, that the total amount of energy emitted or absorbed by a radiating body is always proportional to the frequency of vibration of the body concerned. Another way of saying the same thing is to say that the ratio of the number of quanta of energy emitted to the frequency of the vibration of the source is a constant quantity, and is an integral multiple of Planck's constant "h."

This idea is quite foreign to our ordinary ideas connecting the energy of a vibrating material body with the frequency. For example, if we think of the energy connected with the vibration of a tuning fork, there is no definite relation between the energy it possesses at any moment and the pitch of the tone it emits. The pitch remains the same as the energy dies away. It is difficult to conceive of any ordinary mechanical systems where any such effect could be produced.

The very radical nature of the proposal may, perhaps, be understood better when it is stated that it has since been shown to be at variance with all the previously known laws of mechanics, which have been well established so far as applications to gross matter are concerned. It is pointed out that there is no logical necessity that the same laws which apply to gross matter, where averages are concerned, should also be applicable to single atoms, unless, perhaps, they are in their steady states not radiating energy. This has given rise to the expression "classical dynamics," the attempt being made to distinguish between the laws that we know hold for gross matter, and those as yet unknown laws that may

apply to atoms and electrons while transferring energy.

As another direct result of the proposal it has been shown that motion cannot take place as a continuous process, but that all motion must be thought of as a series of "jerks," so small, of course, that it must appear continuous to all intents and purposes, but nevertheless not exactly so. It is very fortunate that Planck had the courage to lay aside all thoughts of using electromagnetic theory in accounting for these phenomena, because, had he adhered to it, we should probably even now not be aware of the existence of this all important constant, which is proving its usefulness with increasing frequency as time goes on. Having obtained the point of view cited in some of the opening paragraphs, the fact that it introduces us to a new set of conceptions is not disconcerting. It rather offers a new incentive to the theorist, whose work really begins when something new is discovered.

Since there have been no successful attempts as yet to explain the existence of such a thing as Planck's constant, the author will not be accused of presumption in recording certain thoughts that have occurred as offering some

light on the subject, or as possibly offering ways to work out of the maze eventually. The inference just mentioned that all motion takes place by "jerks" must mean, if we interpret it correctly, that something gets from one place to another by stages, dwelling at certain intermediate points in turn but not at others in its path. The statement conveys the idea that the whole time of travel between two distant points is divided up between successive resting places, and that the time required to pass from one stage to the next is zero. This is particularly difficult to believe. It implicitly says that the velocity of something is infinite. Why not better say that the motion is irregular or not uniform, but that the velocity is not infinite anywhere, in which case it would really be continuous after all, and yet retain all the appearances of motion by jerks as stated? Admitting this point of view the flow of energy is also continuous, but may still go in quanta. Some explanation is required why this continuous flow of energy can only stop flowing after a definite number of quanta have passed.

With this modification the thought is that, perhaps, after all when the correct electromag-

netic theory is found, it may be capable of handling the matter. It may be said that certain attempts in this direction look promising at least. To show how this may be requires some attention to details. Imagine that two electrical charges of the same kind and amount revolve in circular orbits at the same speed and in the same direction. Let the two orbits be placed in the coaxial position, having, say, their axes of rotation vertical, the center of the one being directly over that of the other. We need not consider for the present what causes them to revolve. Let the charges be fixed to a single point on the rims of each of two wheels, if we choose.

Electromagnetic theory tells exactly what the force is that one charge exerts upon the other at each instant of time. The direction of the total force that the first exerts upon the second is neither in the line joining the charges, as before stated, nor in the direction of motion of them. The total force may be resolved in any direction we choose. Let it be so resolved along the tangent line drawn to the wheel at the point where the charge is. Now, unless the force resolved along this line happens to be zero, it

will tend to retard or accelerate the motion of the wheel. We have said nothing as yet about the relative locations of the two charges on the two wheels, but, since the velocities are the same they will retain the relative positions they had at the start.

The strange result is obtained from an application of the equations that the two charges may be so situated in their circles that the force which one exerts upon the other along the tangent line is zero, thus tending neither to accelerate nor retard the motion, while that of the other acting on the one is not zero, and tends to retard or accelerate the one. In order that the motion of neither wheel shall be either accelerated or retarded by the action of either charge, it is easy to show that there are only a limited number of possible positions that the two charges may have relative to each other. These positions are approximately the same, namely, the one charge directly over the other; but, for a stable condition it is necessary that each charge shall revolve once, twice, three times, or some integral multiple of times around the whole circumference of the wheel during the time required by light to pass from one charge to the other, that

is, along a direction parallel to the common axes of the two wheels.

Let us now imagine that the wheels are dispensed with, and that the charges represent the two electrons, one in each of two hydrogen atoms. This combination of two hydrogen atoms forms one molecule of hydrogen, and let us say that the two electrons in the molecule act upon each other in the way we have indicated for the charges on the wheels. The distance between the centers of the two atoms is determined by other forces than those mentioned. The translational forces that each atom exerts upon the other along the direction of the axes must be calculated by the same electromagnetic equations. The result is that we are able to show that we obtain a different stable configuration for each of the cases where the electrons make one, two, three, or more whole revolutions during the time that light is passing between the electrons. Each configuration is fixed and stable and differs from each of the others. There is a gradual gradation by steps as the number of complete revolutions increases by a single unit each time during the time that light is passing from one to the other; the dis-

tance between the atoms increases, the actual velocity and consequently the kinetic energy of motion decreases, and the radius of the orbit decreases as well as the frequency of revolution with each step.

This series of molecules has offered a satisfactory explanation of Balmer's and Paschen's series of spectral lines for hydrogen, and in order to make it do so, the values of certain constants in the equations are determined numerically, particularly the actual velocities and consequently the kinetic energy of motion of the electrons. The values of these speeds, beginning with the one-revolution form, are 0.00738, 0.00369, 0.00246, 0.001485, etc., part of the velocity of light. This is the manner in which these speeds of the electrons in the hydrogen molecule previously mentioned have been obtained.

Now there seems to be no experimental evidence for the existence of that form of molecule where the electrons make but a single revolution, Balmer's series demands that all the other forms exist, the fundamental or first of this series starting with the two revolution form, which seems to be that of hydrogen in its ordinary condition. It was the second value 0.00369, it will be remem-

bered, that was compared in a former section with the average speed of electrons in the earth. This matter is confirmed again by comparing the kinetic energy of the electron with the experimental energy of dissociation of the hydrogen molecule into its atoms. The calculated value is 5.348×10^{-12} ergs, and the experimental measurements of Langmuir give 5.8×10^{-12} ergs. This calculated kinetic energy is that for the second form of molecule where there are two revolutions. The energy in the first form is four times as great and does not correspond with Langmuir's value. This indicates that the hydrogen with which he worked must have been in the second form, and thus confirms all the other indications, that from the spectra, and from the earth.

The point is, however, that the kinetic energy of motion is obliged to change over by a certain fixed amount in this kind of a scheme, each time the molecule changes over from one of these definite equilibrium forms to another. It has also been shown that there is a definite frequency of oscillation that will be set up when it changes over from one form to the other, and this frequency depends upon and is proportional to this

energy. That is to say, the ratio of the energy to the frequency produced in changing over, say from No. 2 to any other form, is a constant, and that this constant is equal to Planck's constant "h." This example offers a reason for the existence of such a definite constant without departing from the ideas of electromagnetic theory.

It does more than this, because it offers a suggestion as to the direction in which to work, and gives for the first time a possible mechanism which serves to give us a mental picture of the process. It does not prove, to be sure, that this constant should be universally connected with all atomic phenomena where energy flow is concerned. But, it does not prohibit this from being the case. It does give some insight into the reasons why it appears that motion should take place by "jerks." The revolutions of the electrons in these atoms are many times greater than the frequencies of the light emitted, and the change over from the one form to the other probably takes place in a few revolutions, namely, in a very small fraction of the time of one light wave, and the change once begun must continue until completed, thus giving rise to "quanta," although the energy flow is perfectly continuous.

It is superfluous to remark that these matters are only presented because they seem to offer a single ray of light upon a most obscure phenomenon. They are not established, of course, but, it seems as if some way will eventually be found to make it possible to retain electromagnetic theory as pertaining to the case. At the least it shows that all possible attempts had not been made when Planck decided to lay aside existing theories to explain radiation.

The question has probably occurred to the reader, who has been persuaded to follow the story thus far by alluring promises made at the beginning, when will those attempts at a partial statement of the problem of the structure of matter be made? The author is curious to know what his attitude will be when it is admitted that he is unable to fill the contract. The further we proceed the further away seems the goal.

We have had one thought impressed upon us, however, by the small number of different things that have been considered, that a possible classification of phenomena may be based upon a distinction between the steady states of matter, and those states in which there is a transfer of energy from place to place, or from matter to

matter. Unfortunately for immediate progress, by far the greater number of phenomena we desire to understand are involved with this transfer of energy, and, if there is any truth in the existence of a quantum of energy, no understanding of any of these phenomena is possible without understanding the primary cause of this.

When we eat a dinner a chemical metamorphosis of the food elements is immediately begun; the atoms of the molecules change partners, and in a wonderful manner the right ones find their way to the right places, being requisitioned by some cells and not by others. Any change of partners among the atoms of the molecules is accompanied by an absorption or an evolution of energy in the form of heat. In this case the heat evolved is greater than the heat absorbed, and the bodily temperature is maintained at a nearly uniform value higher than that of its surroundings by means of the energy content of the molecular structures in the food. This subject constitutes one of the great topics in chemistry. The heat energy absorbed or evolved by the change of partners between almost all kinds of known molecules has been carefully measured, but these experimental results have

received as yet no satisfactory explanation in terms of the structure of atoms. We now have the suggestion that, being an energy transfer phenomena, we will not be successful in this without bringing to bear upon it the conception of energy quanta.

Bound up with this is the understanding of the chemical "valencies." Why will one atom of carbon enter into partnership with four atoms of hydrogen and no more? Why are there two or more valencies sometimes possessed by atoms that have the same atomic weight? We do not say by the same kind of atoms, because we have already had the suggestion that atoms of the same atomic weight may differ in kind. When knowledge of these things becomes more exact, it seems quite probable that atoms which have different maximum valencies, even though their weights are the same, may be called by different names. Something is needed to distinguish them.

One of the chief difficulties that the theorist finds in making use of the extensive experimental results accumulated by the chemist is the fact that they deal, with very few exceptions, with combinations of atoms of different kinds. We

need to know also the energy changes involved when a single element alone is present. For example, if we start with two gases, hydrogen and chlorine, each having the same number of molecules, it is possible to unite it all into a compound substance, hydrochloric acid (H Cl). But in order to do it, there must be a change in the total energy content of the two gases, which is dissipated or absorbed as the case may be before they are finally brought to the same temperature after the reaction as they had before it. In the new substance formed an atom of hydrogen has united with one of chlorine. Before the reaction, however, each atom of hydrogen was united to another of hydrogen, forming the hydrogen molecule, and each atom of chlorine with another of chlorine, forming a chlorine molecule. What happened during the reaction was that each molecule of hydrogen was separated into its two atoms, or at least, before the reaction is over, they are forced to part company. This operation requires that work be expended upon the hydrogen. Similarly, work must be done upon the chlorine to tear its molecules apart. Then the hydrogen and chlorine atoms in coming together perform work, and, in forming the

molecules of H Cl, give back again energy. Now, whether or not they give back more energy in thus coming together than the hydrogen and chlorine received in being separated from each other determines the whole question whether, on the whole, we must perform work upon the original gases to produce the reaction, that is, supply the necessary heat, or whether they will perform work for us, by giving out energy in the form of heat. The chemist has merely measured these differences in most cases, and there are too many unknown quantities for the theorist to make easy use of his data.

He needs to know the values of the separate parts, the energy required to separate the hydrogen from the hydrogen, and the chlorine from the chlorine. The experimental result will then give the energy required to separate the hydrogen from the chlorine, with which theoretical results may be compared. There are at present very few of the values known for the single elements. The process of finding them is foreign to the ordinary operations of chemistry. The energy of dissociation of hydrogen has been approximately determined by Langmuir, above referred to, by the study of the behavior of hy-

drogen gas in a bulb containing an incandescent tungsten wire, a physical process rather than a chemical one, if it is now proper to make any distinction at all between them. It is to be hoped that many more of the elements will be added to the list in the near future.

It is difficult to put aside the conviction that, when more of this information is available, certain generalizations will be possible, which will have a very important influence upon our real knowledge of what takes place during transfers of energy on the part of the atoms. This matter of the energy transfer forms evidently one of the principal topics now before us.

Much more might be recited concerning the many experimental observations that have been made in several different directions, but would this recital after all greatly strengthen our main argument that eventually these things may all be comprehended in terms of the structure of the atoms and molecules, and their intimate connection with the aether? It may be thought that an account of this kind is very deficient that does not include an extended review of the subject of radioactivity, which has, perhaps, given us more than any other subject an insight into the

nature of atomic structures. There are works which deal with this subject in detail, to which reference is made, and from which a better understanding of radioactivity may be had than from anything that might be said here.

We have also omitted the many effects of light acting upon matter, the so-called photoelectric effect; the change in electrical resistance of a substance, like selenium, under the action of light; how light affects certain salts, an effect that makes photography possible; and again, the effects of "light pressure" in various ways. Let us hope that many will be induced to look into these matters more attentively now that they have read a brief account of the small beginning that has been made toward a more complete understanding of the wonderful world in which we live.

THE END.

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